

ADVANCED SUBSONIC LONG-HAUL TRANSPORT
TERMINAL AREA COMPATIBILITY STUDY

Volume I—Compatibility Assessment

By Preliminary Design Department

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16. Abstract An analysis was made to identify airplane research and technology necessary to ensure advanced transport aircraft the capability of accommodating forecast traffic without adverse impact on airport communities. Projections were made of the delay, noise, and emissions impact of future aircraft fleets on typical large urban airports. Design requirements, based on these projections, were developed for an advanced technology, long-haul, subsonic transport. A baseline aircraft was modified to fulfill the design requirements for terminal area compatibility. Technical and economic comparisons were made between these and other aircraft configured to support the study. Research recommendations are given in volume II.					
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ADVANCED SUBSONIC LONG-HAUL TRANSPORT

TERMINAL AREA COMPATIBILITY STUDY

Volume I—Compatibility Assessment

By Preliminary Design Department

1.0 SUMMARY

This study identified airplane research and technology necessary to ensure future airplanes capability to meet forecast traffic demand without adverse effect on airport communities. The potential costs and benefits of this research were estimated.

To determine the nature of desired operational features, current airplane noise impact, airplane arrival and departure rates and urban area air quality were forecast to the year 2000 for example airports. Desirable airplane capabilities which would improve airplane/airport compatibility were then postulated and their effects were evaluated quantitatively. The intent of the study was to assume the burden of terminal compatibility to be primarily on the airplane. Possible ground-based solutions were acknowledged but were not specifically studied.

Three specific airports, J. F. Kennedy, O'Hare, and Los Angeles International, were considered to lend realism to the projections. The feasibility of achieving the desirable capabilities was examined by configuring airplanes with the needed design features. Four airplane designs were developed and the changes on airplane weight, performance and economics were assessed. As a final step, the airplane technology development which had been found to be critical to the desired improvement was identified, and the research and development programs necessary to achieve them were defined.

Throughout the contract, meetings were held with airlines, airport authorities, and government agencies, to ensure that the assumptions and recommendations of the study were consistent with their experience and plans. This coordination effort was one of five program tasks. These tasks are summarized in figure 1.

Results of the principal calculations made in this study are given in figure 2. Key points:

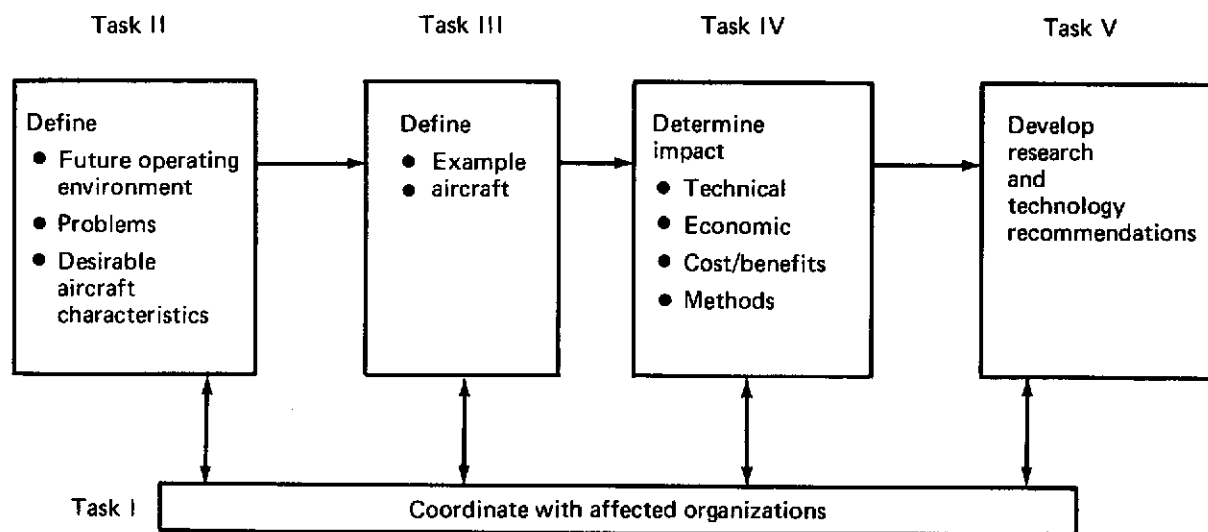


FIGURE 1.—STUDY TASK DEFINITIONS



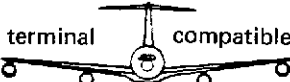





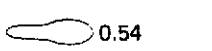


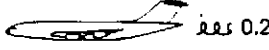



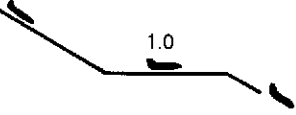
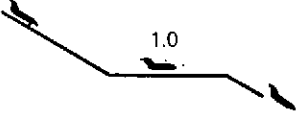
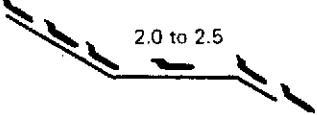
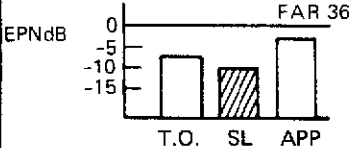
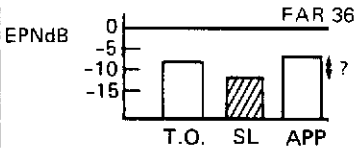
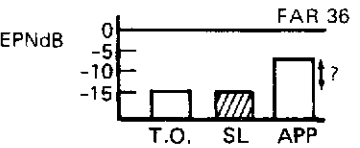
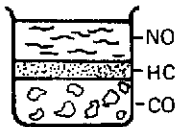

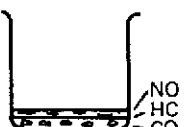

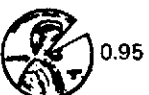
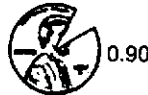



Item	Present technology CWB 	Advanced technology ATT 	Advanced technology terminal compatible TAC 
Projected airport impact			
Congestion Relative peak hour delay—typical airport	 1.0	 1.0	 0.16
Noise Relative 90 EPNdB noise-affected area	 1.0	 0.68	 0.54
Emissions Total pollutant tonnage	 1.0	 0.5	 0.2
Relative airplane characteristics			
Gross weight Takeoff weight	 1.0	 0.89	 0.93
Runway operations Runway efficiency—arrivals/unit time	 1.0	 1.0	 2.0 to 2.5
Noise Relative to FAR 36 station noise	 FAR 36 EPNdB 0 -5 -10 -15 T.O. SL APP	 FAR 36 EPNdB 0 -5 -10 -15 T.O. SL APP	 FAR 36 EPNdB 0 -5 -10 -15 T.O. SL APP
Emissions Kilograms per landing/takeoff operation	 1.0 NO HC CO	 0.46 NO HC CO	 0.17 NO HC CO
Airplane economics			
Operating costs Relative DOC	 1.0	 0.95	 0.90
Net present value Relative dollars	 1.0	 1.45	 2.20

FIGURE 2.—SUMMARY COMPATIBILITY ASPECTS

- a) Congestion at major airports results in considerable inefficiency today and will become worse in the future. Airplane modifications cannot alone solve the problem; however, if sufficient R&D emphasis is applied, one approach to congestion reduction can reduce delay times by 84%. This approach is contingent on an as-yet-undemonstrated solution to aircraft wake turbulence.
- b) Noise restrictions exist today at some major airports. This further compounds the congestion problem. Future noise problems show signs of improvement as newer, noise-designed aircraft replace earlier, less quiet aircraft. Further gains in noise improvement appear possible if vigorous R&D efforts enable projections to be realized at acceptable cost. The use of improved airplane takeoff and approach paths may offer an attractive alternative to extensive engine treatment, particularly when fuel usage is considered.
- c) Aircraft emissions may not be a problem. However, the extent to which such emissions must be considered could not be determined since airport pollution tonnages are difficult to interpret in terms of air quality impact. Today's airport tonnage levels are somewhat evenly divided between automobiles and aircraft; future trends show greater relative aircraft contribution. Oxides of Nitrogen, as a proportion of total tonnage, will increase relative to Carbon Monoxide and Hydrocarbon pollutants reflecting the scarcity of satisfactory control techniques. Research and technology efforts can improve the situation. A terminal compatible airplane assuming advanced combustors, powered wheel, and operating in ground delay-free airports will be 83% cleaner than today's widebody aircraft.
- d) A fleet of terminal compatible airplanes could potentially realize sufficient cost savings due to delay reduction, to more than offset the costs due to incorporation of congestion-reducing design modifications. In fact, the delay savings would offset the costs of the noise and emission modifications as well.
- e) In the absence of vigorous research and technology efforts, the above projections have no basis whatsoever. Moreover, existing problems will be compounded.

Some additional pertinent study results are summarized below.

With respect to congestion, today's traffic demand was found to already exceed the capacity of some major airports at peak hours, and this demand will increase several-fold by 2000. Meeting this demand by airplane changes alone, without additional airports or artificial demand constraints, was shown to be not feasible; a coordinated air transportation system capacity expansion program is required. However, because of the difficulty of increasing both airport size and number, the

maximum potential airplane contribution to increased capacity has been studied. The major bottleneck in the flow of traffic was shown to be the safe interval between airplanes using a runway. This is currently determined by safety considerations related to wing trailing vortex ("wake turbulence") characteristics of large aircraft.

Furthermore, expected advances in ATC, airplane and airport characteristics will cause: (1) "wake turbulence" effects and, (2) the time an airplane must spend on the runway to be even more limiting in the future. The severity of the latter factor was shown to be reduced several-fold by improved automatic braking and steering systems, with passenger comfort and pilot workload setting the limits. The "wake turbulence" (airplane trailing vortex) problem is poorly understood today; one proposed solution was assumed and studied to assess the magnitude of penalty incurred. A 2% takeoff gross weight increase was calculated for all of the congestion-reduction modifications. Extensive research activity to understand the basic physics of vortex formation, strength, stability and means of controlling it is urgently needed.

The present study showed that eventual replacement of current aircraft with a fleet complying with FAR Part 36 (noise levels at specified ground points) will effect a 20% reduction in ground area affected by airplane noise by the year 2000. However, within the study requirement that the noise impact on the community be reduced to an acceptable level solely by changes to the airplane, rather than in combination with improved airport area land use, further reduction of airplane noise was studied. This could be achieved, only with adequate R&D funding, and at increased operating cost, by increased engine and nacelle treatment. In this case, if improvements are also assumed for derivatives of current aircraft, then it was determined that ground areas heavily impacted by noise could be approximately contained within the boundaries of typical large airports by year 2000.

Additional airplane contributions to noise reduction by means of improved flight paths were also studied. Assessed operational and design features included steep descents, shorter takeoff runs and steeper climb gradients, all as means to keep the airplane farther from noise-sensitive areas. Such flightpath flexibility required: shifting the basic airplane design more toward low-speed aerodynamic optimization; the addition of controllable drag devices; and expanded guidance and display systems to maintain safety and accuracy. The results suggest that extensive treatment together with flightpath improvements may be redundant with respect to noise improvement on advanced transport aircraft. Some considerations regarding the best design approach, including an assessment of fuel expenditure, were made, but additional study will be required to settle the question. One major area identified as a current roadblock concerns the lower practical limit on source-noise reduction due to the aerodynamic noise of the airplane interaction with the air. This factor is fundamental and research is needed to determine the level and means of controlling it.

The effect of airplanes on air quality cannot be accurately determined with current lack of knowledge of (1) the effects of individual pollutants on people, and (2) the physics of pollutant motion through the atmosphere. With the characteristics of today's automobiles and factories, the airplane is not a major source of pollution. However, as automobile and industrial emissions are reduced, as the number and size of airplanes increase, and as our knowledge of emittant effects is improved, it will be necessary to review the relative pollutant contribution of the airplane.

This study has shown that engine manufacturer projections of future combustors will enable appreciable reduction of the amount of emissions per unit of fuel burned. In addition, informal discussions with the manufacturers suggest that these gains for new, advanced engines may be achieved at minimal additional cost. Moreover, if airport congestion can be reduced or better coordinated control of aircraft movements on the ground effected, then significant improvement to carbon monoxide and unburned hydrocarbon emissions will be achieved since these are primarily produced during ground operation. Further reduction, if necessary, has been demonstrated by incorporation of internally-driven wheels as an alternative to main-engine taxi propulsion. This powered-wheel concept was shown to be not cost-competitive with engine combustor modifications since the latter have been estimated to incur zero weight, performance or cost penalty. It does become competitive if combustor modifications add 10% to engine cost, however. More importantly, the powered wheel may help to achieve a successful low-pollutant combustor design which typically must confront conflicting requirements between carbon monoxide/hydrocarbon reduction and reduction of oxides of nitrogen. Use of the powered wheel could allow a combustor design biased towards control of the nitrogen oxides. It may also provide ground movement flexibility in the terminal area with less ground equipment.

The airplane configuration task exposed a number of interacting design requirements imposed to handle the various congestion, noise and emission modifications. Drag brakes, for example, were incorporated to enable steep descent to achieve approach noise reduction. However, these brakes might in fact add to the airplane "airframe" (nonpropulsive) noise. As another example, the use of the outboard engine at high levels of engine airflow to control wake turbulence basically conflicts with both the engine source noise requirements on approach and the use of a high-aspect ratio wing to improve takeoff noise.

Generally, potential design resolution of conflicting requirements was achieved. One exception to this concerned the study to provide RTOL (reduced takeoff and landing) capability to the terminal-compatible airplane. The intent was to provide greater flexibility for routes structured to avoid the most congested airports. Use of an overwing propulsion installation on a four-engine configuration to achieve improved takeoff lift coefficients resulted in significant cruise penalties. The overwing installation further conflicted directly with the wing vortex control technique of an extreme spanwise outboard engine location. This conflict was not resolved. However, the current

study was also unable to determine any significant potential economic advantages of the long-range airplane with RTOL capability.

The airplane that was designed to meet the terminal area goals is heavier than its non-terminally-configured counterpart, weighing about 3% more. However, economic savings associated with the reduction in delays due to its higher traffic flow capabilities more than offsets this factor, and the Direct Operating Cost is calculated to be 9.2% lower than for a reference advanced technology airplane designed primarily for the cruise condition. This is in addition to the less easily accountable benefits of the noise and emission reductions to the community at large.

Volume 2 of this document contains the complete list of Research and Technology recommendations: key aeronautical items (fig. 3) are:

- a) Wake vortex physics, detection, and control
- b) Airframe noise prediction and control
- c) Engine design for the combination of low noise and low emission of pollutants at both high- and low-thrust levels,
- d) Guidance, control and display requirements for the tightly-sequenced combination of steep descent, landing, rapid deceleration, and high-speed turnoff, all during adverse visibility, wind, and runway surface conditions.
- e) Drag devices to enable steep descent operation.

While this study was primarily aimed at potential airplane improvement, various characteristics of the rest of the air transportation system and related areas which are necessary or desirable were recognized. Prominent among these are:

- a) Ability of the airport terminal to handle larger numbers of airplanes and people,
- b) The continued development of an Air Traffic Control System such as the tentatively planned Advanced Air Traffic Management System,
- c) Coordinated development of secondary airports and appropriate airplanes and surface transportation links to supplement the primary airport/airplane network,

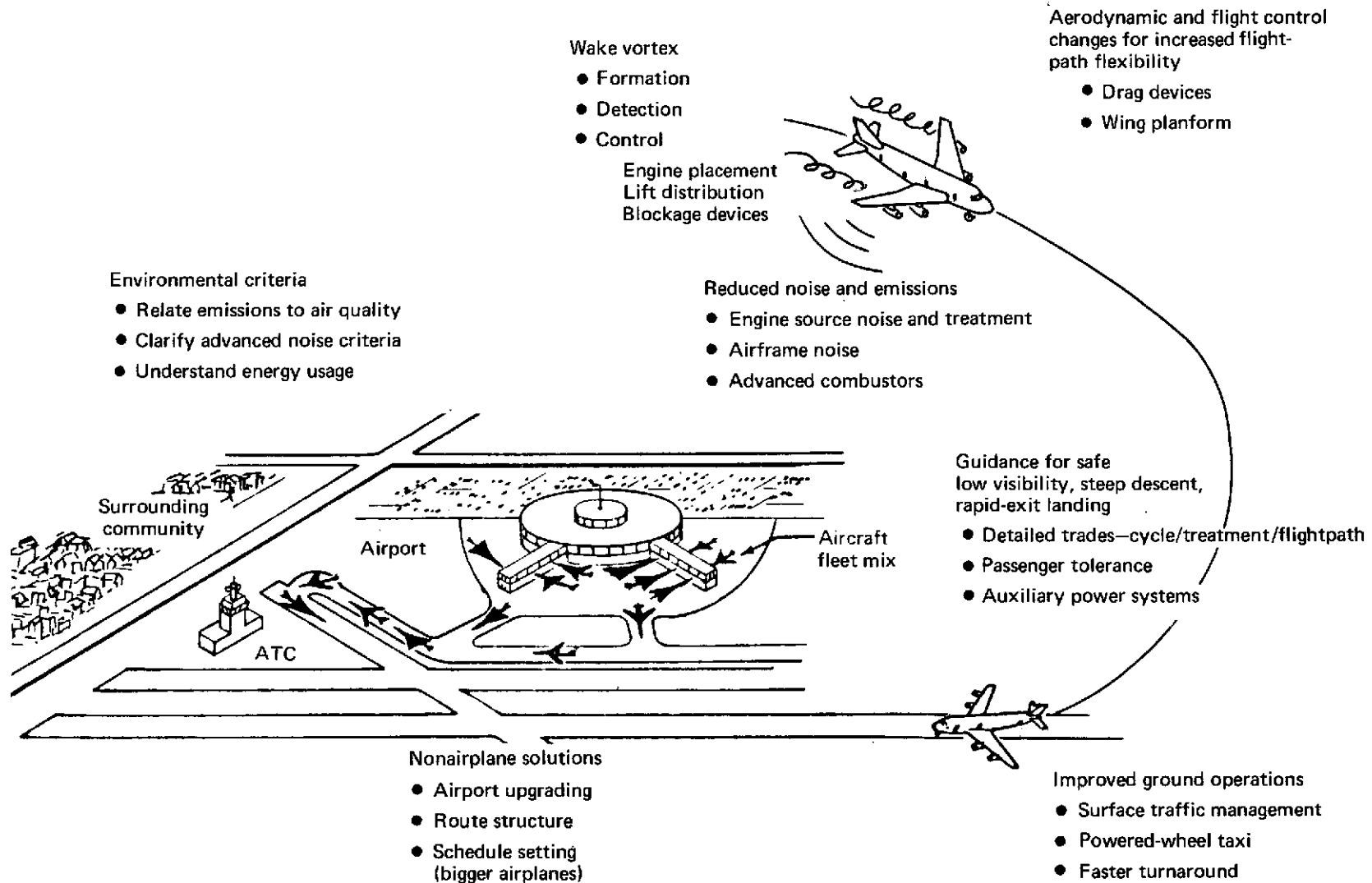


FIGURE 3.—TERMINAL COMPATIBILITY SOLUTIONS AND KEY RESEARCH

- d) Development of technology and broad economic and social value models leading to rational, cost-effective noise and pollution limits for each source.
- e) The initiation of studies leading to improved awareness of the relationship of energy use to aircraft design in general and terminal compatibility in particular.

The overall conclusion to be drawn from this study is that major problems associated with airplane terminal area operations can be predicted, that a number of potential airplane improvements can help to solve these problems, and that extensive, timely research and development is necessary to make such improvements technically and economically feasible.

2.0 INTRODUCTION

2.1 STUDY OBJECTIVE

The objective of the Terminal Area Compatibility Study "... is to identify the aeronautical aspects of advanced long-haul subsonic transports which could help solve the anticipated noise, emission, safety, low visibility, and congestion problems in the terminal area portion of the U.S. National Aviation System during the 1980-2000 time period and determine the required research and technology." The emphasis of the study was *airplane technology* applicable to improved terminal area operations for advanced, long-range aircraft. This study is a follow-on to a previous NASA program entitled the "ATT" or Advanced Transport Technology program (ref. 1). That program emphasized assessment of various advanced technology airplane features, including use of supercritical airfoil technology to increase subsonic airplane cruise speed. One criticism of that study was that the advantages of increased cruise speed might, in fact, not be realized on future aircraft because of current bottlenecks and problems in the airport terminal area. This observation led to the current study, with emphasis on the congestion, noise and emission problems of aircraft in and around principal airports. This emphasis represented a somewhat different orientation towards airplane design since normally airplane efficiency is the principal concern. Therefore, it was desired that an initial brief study be conducted to identify the research and technology areas of principal interest.

2.2 STUDY SCOPE

The scope of the study is illustrated by figure 4 which shows a typical airplane trip from the viewpoint of the passenger.

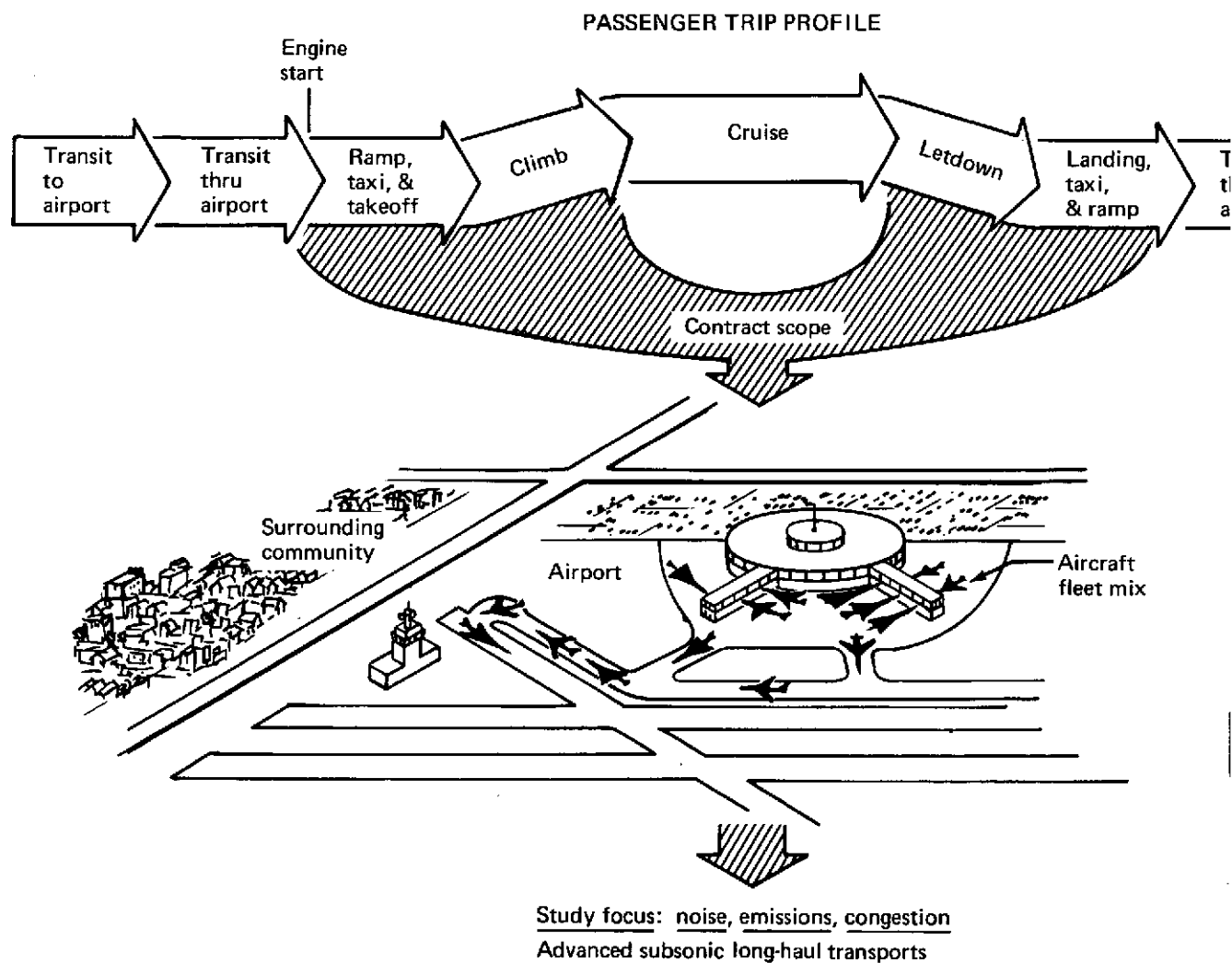


FIGURE 4.—PROGRAM SCOPE

For the current study, by contract definition, the emphasis has been directed to the airplane. Thus, the scope of the present study does not deal with or analyze all of the pictured events. Rather, efforts have been confined to those necessary to determine the research areas appropriate to airplane technology. For this reason, it was deemed sufficient to consider only those airplane operations which are contained between engine start-up and engine shut-down.

Nevertheless, even this restricted study scope, when operations are projected out to the 1980-2000 time period, required consideration of a number of items including: the type of fleet mix which may be flying in that time; estimation of the potential impact of aircraft noise and emissions on the surrounding airport community; and, a projection of the air traffic control system which is, and will be, instrumental in affecting the airplane trip profile.

The present study was an 11-month effort which encompassed five specific tasks illustrated in figure 5. A brief description of these follows.

Task I involved coordination of the study results with interested groups comprising various elements of the air transportation system. These groups included the NASA, engine manufacturers, airlines, various airport authorities, and FAA personnel both in regional offices and at the FAA headquarters in Washington, D.C. The intent of this task was to seek the advice of these groups on the goals, proposed methods, and eventually the results which were achieved in this study.

The bulk of the technical effort expended in the study was contained in tasks II, III, and IV. Figure 6 depicts these schematically. Task II, Compatibility Definition, sought to project the impact of future aircraft operations on typical large major urban airports to evaluate characteristics, desirable in an advanced aircraft, to promote improved terminal compatibility. The method included: making traffic projections out to the year 2000; refining these projections for specific airports of interest; projecting the future air traffic control technology and environment; and finally, combining this information to estimate future congestion, noise, and emission problems for the airports of interest. As shown in figure 6, studies were made of the impact for each of these characteristics under several sets of assumptions. A baseline assumption, included in all of the task II projections was that *nothing* would be done to the operational characteristics of the advanced aircraft beyond the capability provided by current airplanes. Under this assumption, and under the driving force of increased traffic projections, calculations were performed to study how current congestion, noise and emission problems might be compounded. Beyond this, several different "Futures" were then projected. Each of these futures consisted of increasingly advanced technology assumptions concerning the capability of the airplane, the community, the airport, and the air traffic control system. These advanced technology futures were then evaluated with respect to goals defining "assumed-satisfactory" levels of congestion, noise, and emissions. These data were compiled as schematized in figure 6, showing the potential improvement to

airplane/airport compatibility. From these studies, broad desirable characteristics were inferred to which the terminal-area-compatible airplane might be designed. Identification of these characteristics was the final output of task II.

Task III, Compatible Airplane Definition, consisted of configuring an airplane designed to include features for terminal-area-compatibility. To accomplish this, a Mach 0.9, 200-passenger, 5560-km (3000 nmi) range airplane, previously developed under the ATT contract, served as a baseline configuration. Based on the desirable characteristics identified in task II, design modifications were made to the baseline airplane. Since it was not within the study scope to develop detailed design trades, the modifications were based on brief studies into each of the technology areas of interest. In many cases, design decisions were made on the basis of Contractor experience and sound engineering practice. The final output of task III consisted of definition of the TAC airplane.

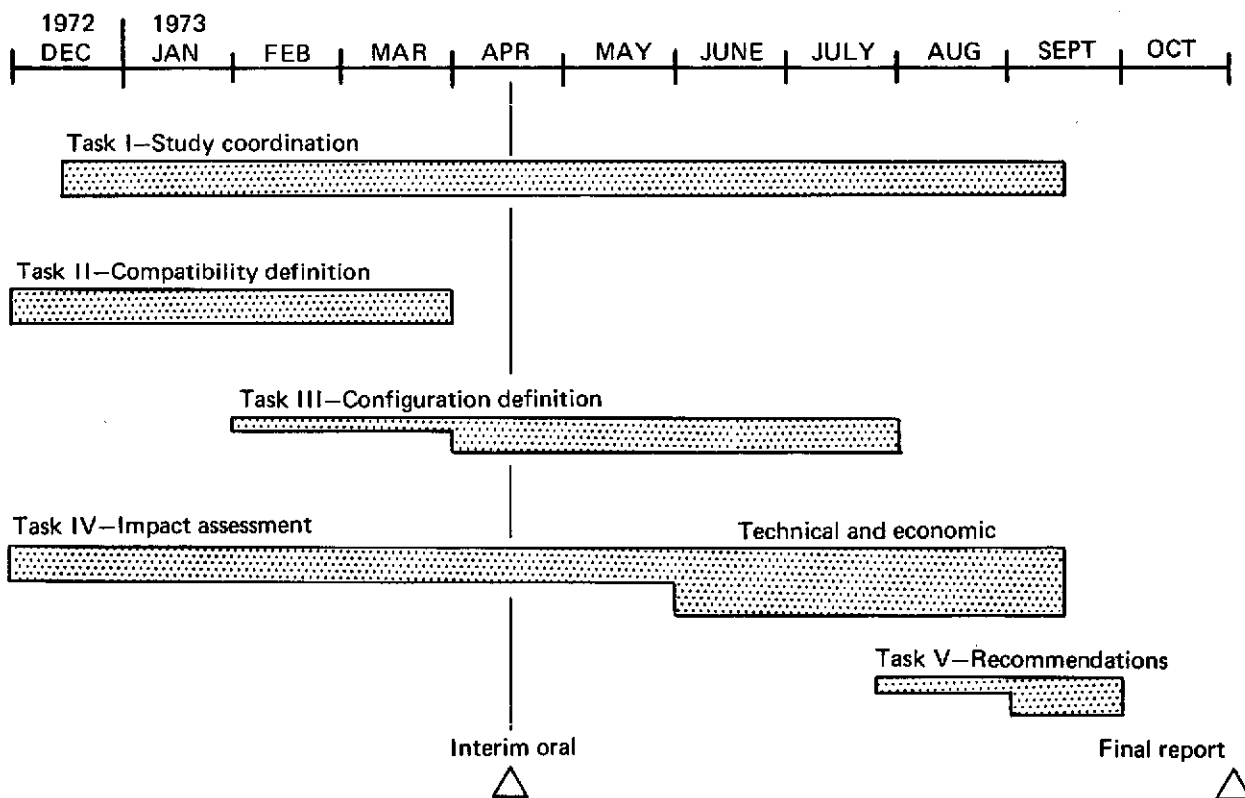


FIGURE 5.—PROGRAM SCHEDULE AND RELATIVE EMPHASIS

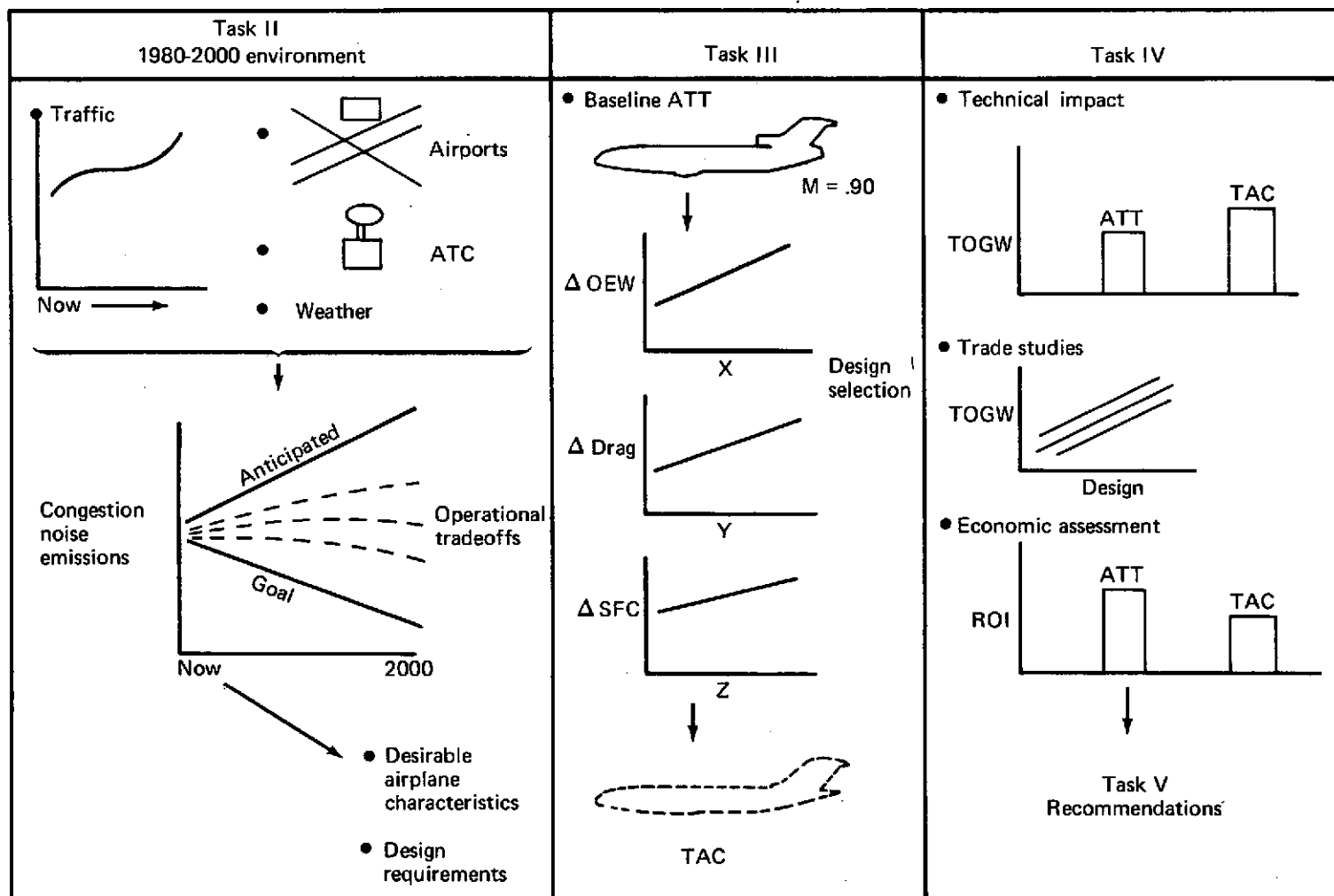


FIGURE 6.—STUDY APPROACH

At mid-point in the current contract, an addition to the study was negotiated to include an assessment of the TAC airplane under a further restriction that the airplane be capable of using 1520-m (5000-ft) runway lengths. Thus, a second airplane, designated TAC-RTOL (a reduced takeoff and landing version of the TAC airplane) was also configured. In addition, a third airplane was designed which used current technology and operational procedures. This airplane was based on current widebody transport design. Configuration of these airplanes concluded task III.

Task IV, Impact Assessment, evaluated the technical and economic impact of the design modifications introduced to the baseline airplane to provide terminal area compatibility and to provide the RTOL capability. Since all aircraft were configured for the same payload and range, an assessment of the impact was made by comparing the baseline and the TAC airplanes in terms of airplane takeoff gross weight. Minimum takeoff gross weight, TOGW, is then a figure of merit of the airplane's efficiency. Beyond that, however, an economic assessment in terms of airplane direct operating costs (DOC) and net present value (NPV) were also made. Moreover, separate accounting was made of each of the "terminal-area" airplane modifications so that assessment could be made separately for each of the design features added to provide terminal compatibility. The task IV efforts also included several brief trade studies which were intended to review and reassess some of the design decisions which were necessarily made rather arbitrarily in task III.

Task V involved distilling the results of the complete study into a series of recommendations identifying research and development which: (1) showed cost-effective potential; and (2) were found necessary to support the concept of "terminal-area-compatible" aircraft. As noted earlier, these recommendations constitute the principal output of the study and accordingly, have been documented separately under a second summary volume developed under the current contract.

This summary document is organized as follows: Principal results of the coordination activity conducted under task I are given in section 4.0. Section 5.0 contains the highlights of the airport impact study conducted under task II and identifies the principal design requirements inferred for development of the terminal compatible airplane. In section 6.0, the results of task III are presented, including: (1) a summary assessment of four airplanes developed under the current contract; (2) identification of the principal technology assumptions used to develop these airplanes; (3) a separate description of the terminal area compatibility modifications which were made; and (4) an assessment of the design change requirements for RTOL capability. The task IV results including both the technical and economic assessments are given in section 7.0. Section 8.0 presents a brief overview of the summary R&D recommendations developed as a result of these studies, more details of which are contained in a separate document, summary volume 2. In section 9.0, the principal conclusions and recommendations reached under the study are summarized.

3.0 SYMBOLS AND ABBREVIATIONS

AR	wing aspect ratio
APU	auxiliary power unit
ASM	air seat mile
ATA	air transport association
ATC	air traffic control
ATT	advanced technology transport
Awet	airplane wetted area
BPR	engine bypass ratio
CO	carbon monoxide
Cw	mean aerodynamic wing chord
CWB	current widebody
DOC	direct operating cost
EI	engine emission index
EPNdB	effective perceived noise, decibels
g	gravitational acceleration
HC	hydrocarbons
ILS	instrument landing system

Kg	kilogram
km	kilometer
L/D	lift-to-drag ratio
M	Mach number
MLS	microwave landing system
NEF	noise exposure forecast
NOx	oxides of nitrogen
NPV	net present value
OEW	operating empty weight
OPR	engine overall pressure ratio
ROI	return on investment
RPM	revenue passenger mile
S	wing or tail area
SAS	stability augmentation system
SFC	specific fuel consumption
STM	statute mile
TAC	terminal-area compatible
TAC-RTOL	TAC—reduced takeoff and landing

t/c	wing thickness-to-chord ratio
TOGW	takeoff gross weight
T/W	airplane thrust-to-weight ratio
T4	engine turbine temperature
V _{app}	approach speed
V _s	stall speed
WCP	wing chord plane
W/S	airplane wing loading
η	dimensional spanwise wing coordinate
Λ	wing sweep
σ	statistical standard deviation

4.0 TASK I—STUDY COORDINATION

4.1 INTRODUCTION AND SUMMARY

Task I of the TAC study called for coordination of the Contractor activity with “representatives of airline, airport, and traffic control organizations to acquaint them with the intent and progress of the study and to gain their cooperation where necessary.” In fulfilling this obligation visits were made to the airports under study. Discussions were held with both municipal airport authorities and local FAA personnel at these installations. Status briefings were also given at FAA Headquarters, Washington, D.C. and to the DOT. In addition, several detailed technical meetings were held with representatives of some of the major United States airlines. Figure 7 shows the geographic distribution of the visits made during this study. Two rounds of visits were made. The first, early in the program, requested information, data, and suggestions for inclusion in the study. A later visit reported on the study when results were becoming apparent and before conclusions were finalized.

4.2 DISCUSSION

Cooperation of the various organizations was excellent and is gratefully acknowledged. It should be noted however, that none of the parties listed was contractually obligated to this study. Comments, therefore, varied from offhand opinions to studied observations. For the purposes of this document, the most relevant comments directed to the contractor have been summarized in section 4.4. The reader should be aware that often conflicting views were offered between airport and airline personnel. In many cases, divergent opinions were voiced even between airline-to-airline or airport-to-airport representatives. The comments expressed in section 4.4 are directly as voiced during these discussions. The conclusions drawn, however, reflect a consensus of opinion from all the discussions as interpreted by the Contractor.

As indicated in section 4.4, numerous comments were made relative to the scope of the study and its emphasis on airplane-oriented solutions. The point was that while airplane design changes were certainly desirable these should be undertaken in reasonable balance with ground-oriented improvements. Another topic that produced considerable comment included the various procedural changes adopted for terminal compatibility and connected with airplane approach operations, e.g., steep approach, close spacing, rapid deceleration, and high-speed exit. These comments could be summarized by saying that the proposed changes would have to be carefully demonstrated and established to be safe and feasible before being put into practice. From an environmental point of view, airplane noise was universally acknowledged to be of primary concern.

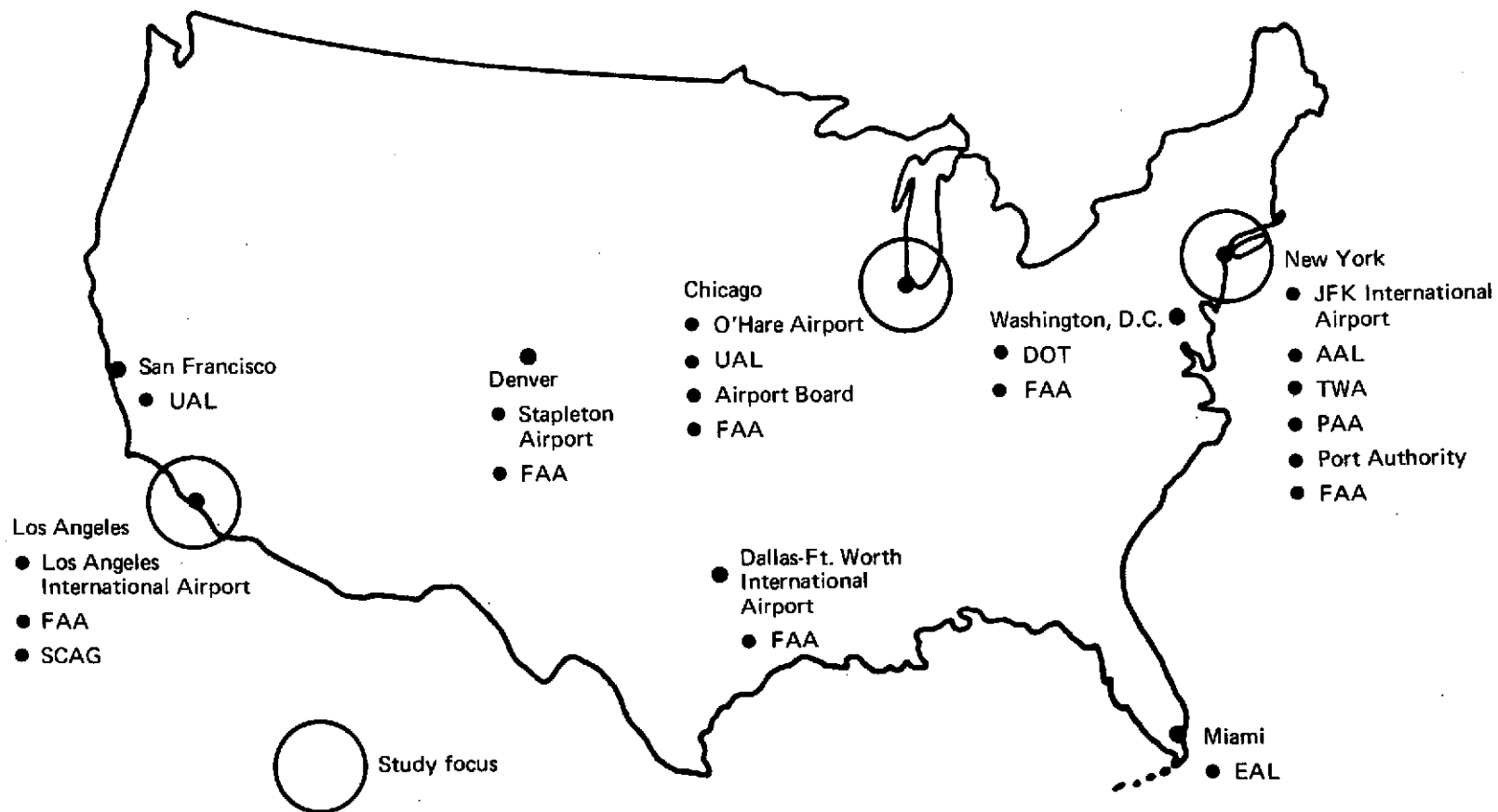


FIGURE 7.—TASK 1—COORDINATION CONTACTS

However, substantial credit was given to the well-demonstrated and well-received improvements of the widebody jets. The study emphasis on aircraft emissions generally evoked little response. Most of the coordinating groups were familiar only with the smoke question and aware that this problem has essentially been solved.

4.3 TASK I CONCLUSIONS

One overall conclusion of some importance is that general agreement exists that future expansion of the airline industry can be severely hampered by congestion and environmental constraints; there is no general agreement on a specific course of action to prevent this. Other specific conclusions derived from this task, as distilled from the numerous comments received, follow:

4.3.1 Congestion

- a) Congestion relief opportunities and requirements are broader than just airplane design modifications.
- b) General agreement exists as to existence and cost of congestion problem but there is no unanimity regarding acceptable solutions.
- c) Wing tip vortex is a serious operational constraint.
- d) No new airport or significant expansion of existing airports should be assumed.

4.3.2 Noise

- a) The noise problem is real and immediate. Recently manufactured aircraft designed for reduced noise have already improved the situation considerably.
- b) The general attitude toward noise abatement procedures is a willingness to listen but a "show me it's safe and acceptable to passengers" attitude.
- c) Lack of unanimity exists regarding noise annoyance indices.
- d) Noise reduction by airplane and engine modifications results in economic penalties.

4.3.3 Emissions

- a) Most see emissions control as “answer in search of a problem.”
- b) Automobile impact was believed predominant even within the airport confines.

4.3.4 General

- a) Some disagreement was expressed with respect to study forecast of number and size of airplanes.
- b) Revisions to economic evaluation methods of advanced systems was deemed desirable.

4.4 PERTINENT COMMENTS ON TAC STUDY

4.4.1 General

- a) Study scope is too narrow—ground-based improvements more likely to solve congestion problem than airplane improvements.
- b) Passenger count is higher but operations count is lower since advent of jumbo jets.
- c) Wake-turbulence impact has partially offset congestion reduction of jumbo jets.
- d) Airports cannot handle bigger airplanes from standpoint of facilities and passenger convenience.
- e) Cost to airlines of noise reduction is not being considered realistically in some of the schemes proposed for existing aircraft.
- f) Noise and lawsuits are the principal preoccupation of many airport managements.
- g) Traffic projections are too high.

4.4.2 Air Traffic Control

- a) Lots of safety demonstration necessary before close spacing on approach will be accepted by pilots and airlines.
- b) Two-segment approaches, if initiated, should be initiated at all airports by all airplanes at the same time as a safety factor; consider pilot training.
- c) Wake turbulence is the key to improved runway operations.
- d) Don't solve congestion problem by "schedule" spreading.
- e) Scheduling accommodation by airlines is in the cards.
- f) Airline accommodation on scheduling plus bigger aircraft will negate congestion problem.
- g) Delay problems due to gate, ramp and taxiway congestion.
- h) Projected ATC upgrading schedule may be too optimistic.
- i) Intercontinental carriers have to carry multiple equipment for multiple traffic control systems.
- j) O'Hare "peak" hour is 11 hr long.
- k) How do we integrate with STOL: (1) airplanes, (2) airports.

4.4.3 TAC Aircraft

- a) Design should anticipate no change at airports.
- b) Airplanes should be designed to be good neighbors to reduce community pressures restraining airport growth.
- c) Good initial climb capability needed for noise reasons.
- d) Better flight path control good for noise abatement and congestion reduction.
- e) Visual pollution (smoke) was offensive but is being corrected.

- f) Skepticism expressed toward concept of in-flight APU.
- g) Adequacy of NEF (noise exposure forecast) annoyance index was questioned.
- h) Powered wheels could be useful beyond emission control function.
- i) Airport pollution believed due to cars, not planes.
- j) Not too many advantages seen for powered wheels.
- k) Sees good promise for powered wheels for emission and ground equipment reduction.
- l) High deceleration and high-speed turnoffs commonplace at Melbourne, Australia.
- m) Delay reduction can help airlines operate with fewer airplanes.
- n) Airports not subject to much pressure for pollution reduction.

4.4.4 ATT Study

- a) Inadequacy of ATA formula for evaluating advanced technologies
- b) When “hidden” costs are discovered, some advanced technology items are likely to be discarded.

5.0 TASK II—COMPATIBILITY DEFINITION

The objective of task II was to identify broad desirable characteristics desired of a terminal-compatible airplane. Terminal-compatibility for this contract was defined to mean reduction of the congestion, noise, and pollution aspects in the airport terminal portion of the air transportation system to acceptable levels. Identification of desirable aircraft characteristics was accomplished by the following steps:

- a) Three airports representative of major urban terminal areas were identified.
- b) Discussions were initiated with representatives of the airports and other interested parties (e.g., airlines, FAA and DOT) to elicit advice.
- c) The traffic growth of these airports was determined for the time period 1980-2000 assuming no constraints to traffic growth.
- d) The expected traffic composition was defined considering current aircraft life expectancies and the introduction of future aircraft in the form of advanced technology transports (ATTs).
- e) Airport ground facilities and air traffic control environment were projected for the time period of interest.
- f) Separate studies of the impact of fleet operations on congestion, noise, and emissions were undertaken.
- g) Goals were defined, for the purpose of this study only, against which the congestion, noise, and emission impact could be assessed.
- h) Separate airplane related integrated studies were undertaken selectively to broaden the perspective from which desirable characteristics could be inferred and to help understand the interaction between congestion, noise, and pollution.
- i) Consideration was then given to the results of the separate congestion, noise, and emission studies; the integrated studies; and the advice received in the various visits to interested parties.
- j) The final set of desirable characteristics was then assembled (quantified where possible but qualitative in some cases).

5.1 FUTURE TERMINAL AREA OPERATIONS

5.1.1 Results of Traffic Forecasts

Traffic data were developed and analyzed generally in terms of: airport; aircraft seat size; representative aircraft categories; annual, daily, and peak-hour movements. Figure 8 is representative of this data and illustrates the relative levels of traffic growth projected. This figure shows the basic forecast of expected revenue passenger miles for U.S. domestic operations. The data are in close agreement through 1985 with forecasts of the ATA as given in reference 2, "Industry Report, Airline Demand Forecasts, July 1969." The data beyond 1985 is an extrapolation based on Contractor predictions. It is consistent with a declining growth rate of 9.2% in 1975 to 2.4% in the year 2000. The estimated number of originating passengers and the average stage length of their trips are also shown in the figure. These data form the basic forecast from which the more detailed calculations were made. Based on them, more specific calculations were made to serve various purposes. For example, the basic forecast together with historical data relative to operations at the three specific airports of interest were combined to develop the data shown in figure 9. This figure illustrates peak-hour operations to the year 2000 for both commercial air carrier operations and general aviation operations. The forecasts are shown relative to current IFR capabilities. These data were used extensively for the congestion studies.

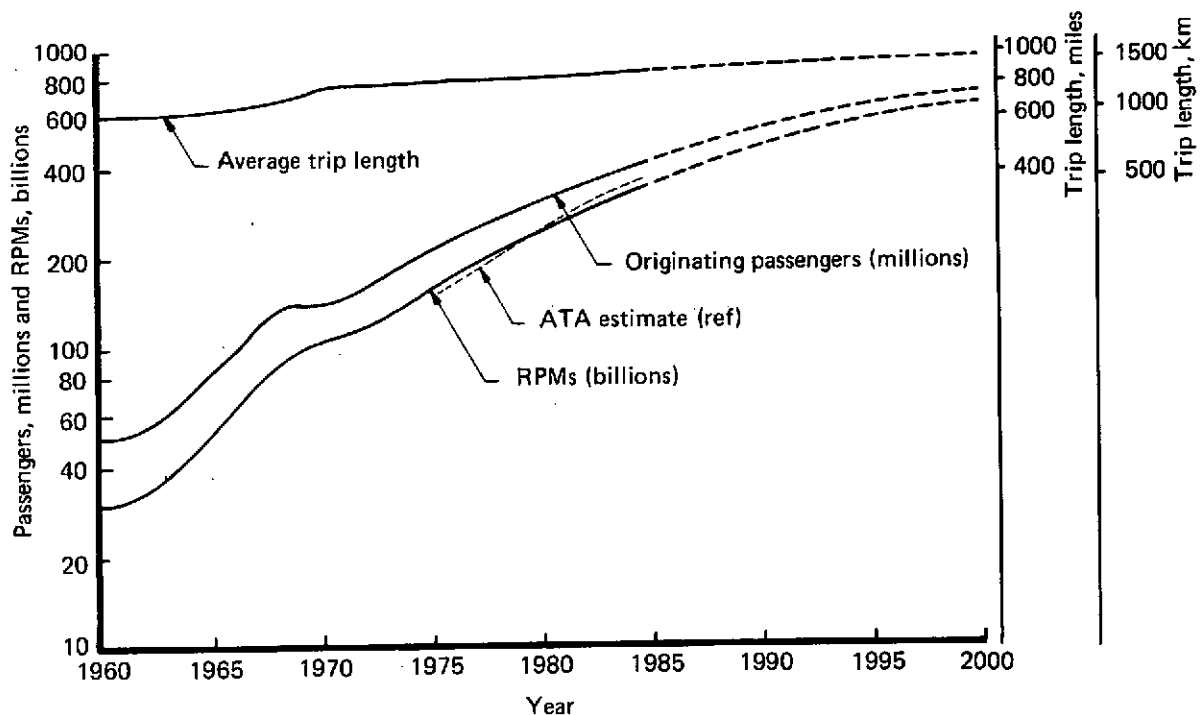


FIGURE 8.—U.S. DOMESTIC RPMs, ORIGINATIONS, AND TRIP LENGTHS

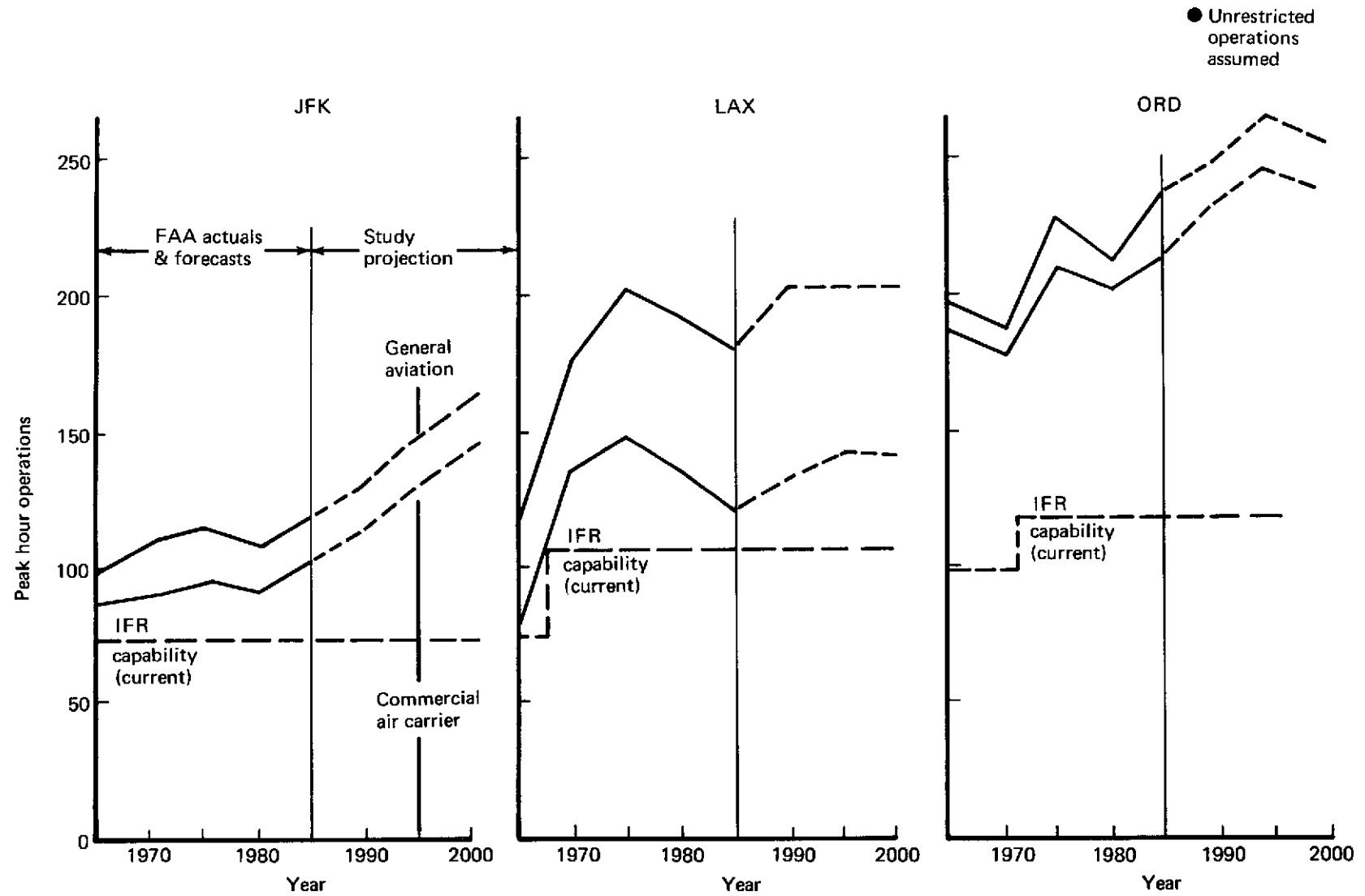



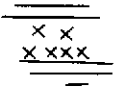
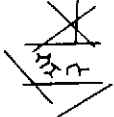
FIGURE 9.—PEAK HOUR MOVEMENTS—JFK, LAX, ORD

Other variations of the basic data were also developed. For example, the noise and emission assessments are affected by propulsion characteristics assumed for the aircraft fleet. To serve this need forecasted operations were broken down according to 12 aircraft-type categories differentiated by engine type. The principal components of this fleet included: representations of existing first-generation narrow-body aircraft; several groups comprising today's second-generation high-bypass ratio-engine turbofan aircraft; and three categories of advanced ATT aircraft in seat sizes of 200, 400, and 800 passengers, respectively.

5.1.2 Study Airports

As noted earlier, to provide focus for the study three specific airports were selected to serve as the basis for airport impact assessment. It should be stressed that the purpose for identifying three separate airports was not to study the potential problems of the individual airports per se, but rather as a useful way to make a general assessment of airport operations in the year 1980-2000. Several characteristics of these airports are shown in table 1. As seen, in terms of itinerant operations, a category which most represents the level of commercial aviation activity, the three airports selected rank first, second, and fifth in terms of total domestic aircraft operations.

TABLE 1.—STUDY AIRPORT CHARACTERISTICS

Terminal—airport	Itinerant operations	Total operations	Runway layout
New York—John F. Kennedy (JFK)	388,829 (5th busiest)	11th busiest	
Los Angeles—Los Angeles Int. (LAX)	510,801 (2nd busiest)	5th busiest	
Chicago—O'Hare (ORD)	628,013 (Busiest)	Busiest	

It is clear that a study of airports JFK, LAX and ORD did not provide a fully representative picture of all airports throughout the country since these three are among the largest urban airports in the world. They were nevertheless distinct in a number of ways and served as a useful basis for study calculations. For example, JFK airport is rated fifth in itinerant operations, but is contained within the New York hub area consisting of three major airports which individually are rated in the top 20 busiest airports. As shown in table 1, the airport layout of JFK consists of two sets of parallel runways. One pair of these runways exceeds the current runway separation requirement of 1520 meters (5000 ft) for simultaneous IFR operations. However, independent simultaneous operations are not permitted due to the airspace conflicts with LaGuardia and Newark, both situated within close proximity to JFK. This proximity tends to lead toward airspace conflicts and thus considerable care is required in programming air traffic control operations.

All four LAX runways are located in an east-west direction guided by consideration of the prevailing winds. Two of the four LAX runways are sufficiently separated to permit independent parallel runway operations. LAX also has some other interesting features, particularly in connection with air pollution in that the terrain and climate favor the persistence and intensification of pollutant emissions. The warm sunny weather encourages the formation of photochemical smog conditions among the worst in the country. The airport is surrounded on three sides by noise sensitive areas and has possibly the severest noise problem in the nation. In mid-1973 a runway preferential-use program was initiated to shift all aircraft traffic between 11:00 p.m. and 6:00 a.m. to over-ocean approaches and departures except during adverse wind conditions. During these periods only those aircraft complying with FAR Part 36 (dealing with the aircraft noise) will be allowed to land or take off to the east. It is clear that between weather conditions on the one hand and noise considerations on the other, the effective available airspace is decreasing in spite of the increased operational requirements.

Chicago's O'Hare airport (ORD) is the busiest terminal in the U.S. In terms of adverse weather, O'Hare sits in the middle of one of the stormiest sections of the country, exposed to active passage of high and low pressure systems on a regular basis. In addition, Chicago experiences numerous thunderstorms, and occasionally experiences large snowfalls associated with the meteorological aspects of the adjoining Great Lakes.

In summary, with respect to the goals of the current study (i.e., an assessment of congestion, noise, and emissions), these three airports selected for study offered a wide variety of conditions from which to infer those capabilities which might usefully be designed into future aircraft in order that the national aviation system realizes its potential growth.

5.1.3 Air Traffic Control Environment

An orderly progression was assumed from today's ATC system through the Upgraded Third Generation System as laid out in current FAA planning to an estimate of the Fourth Generation 1990-2000 system (see ref. 3) still in the planning stage. In most cases, where the details of ATC environment affected the airplane, the Fourth Generation System was assumed as being appropriate to the time when terminal area problems will be most severe. Figure 10 illustrates the projected chronology.

The basis of the Fourth Generation Advanced Air Traffic Management System (AATMS) is the need to handle the large amount of projected traffic safely and efficiently. The salient features which meet this need are listed below.

- a) The basic control of traffic is centralized and automated as far as practical to minimize the number of controllers and the intercontroller coordination required. Strategic control is used, with appreciable portions of an airplane's flight path transmitted to it at a time, in advance, to minimize the need for constant communication and real-time conflict resolution.
- b) A digital data link is used for all normal communications to minimize controller and crew workload and chance for error.
- c) The microwave landing system (MLS) provides navigation inputs in the terminal area for multisegment curved approaches.
- d) En route navigation is provided by the Omega system, with local corrections provided as needed. This gives continuous, universal coverage.
- e) Surveillance is by a satellite-based multilateration system which provides complete geographic coverage on all aircraft, completely independent of the navigation system.

5.2 AIRPORT IMPACT ASSESSMENT RESULTS

The current study contract called for separate informal documentation of the whole of the task II effort. For continuity, an abbreviated version of this material is presented here.

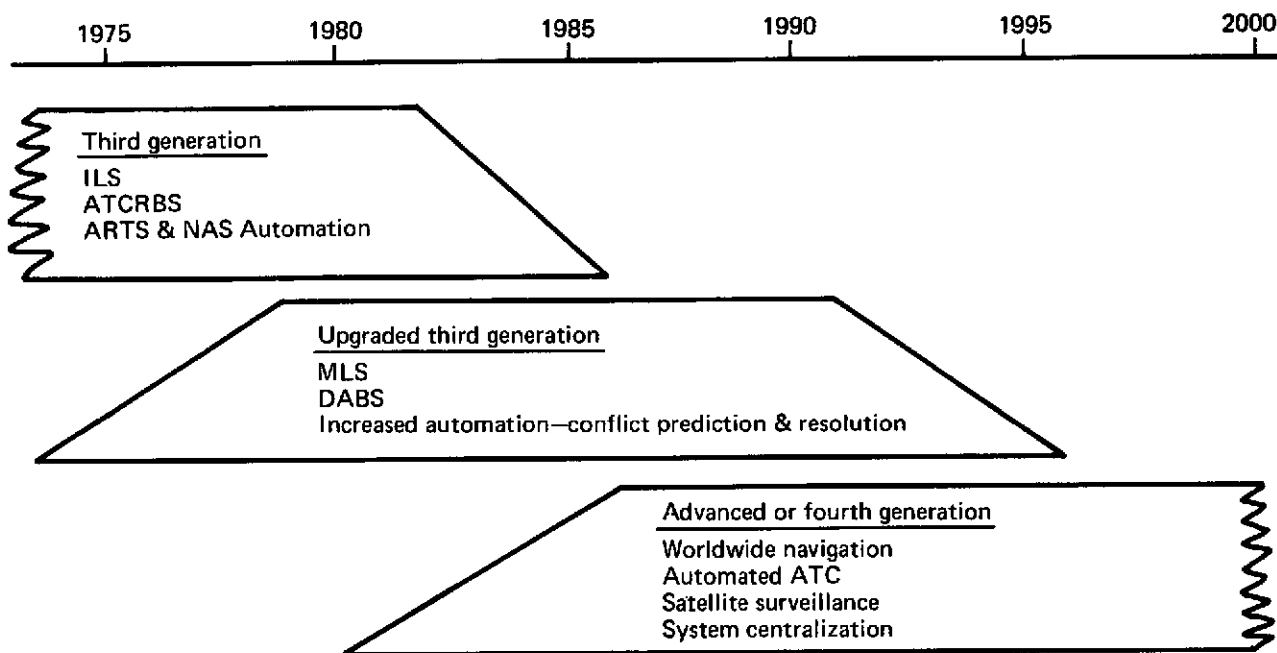


FIGURE 10.—PROJECTED ATC ENVIRONMENT

Figures 11 through 13 illustrate the impact of increased traffic on congestion, noise, and emissions to the year 2000.

Figure 11 shows the congestion picture in terms of average busy-hour delay plotted against year. These data were developed on the basis of a computerized model which simulates runway operations representative of existing and projected airport operations. The model determines numerical levels of runway rates consistent with a specified traffic demand. The predicted runway rates depend upon a number of operational parameters relating to aircraft and ground capability. For example, the model is sensitive to the separation requirements (in miles, say) assumed between two aircraft on approach. In addition, the model is sensitive to other airplane design parameters such as: braking capability of the airplane; speed at which runway turnoff is made; the accuracy in time with which the airplane can be assumed to position itself at a given point in space; etc. The model is also sensitive to such other operational parameters as approach speed of the airplane, whether independent parallel runway operations can be utilized, and others.

For the purposes of the current study, some 1000 computer runs were made considering a matrix of parameters. These data were then analyzed for the various cases to establish the corresponding ability of the airport to handle the projected operations. Figure 11 illustrates the results of these calculations for five specific combinations of assumed parameters. These five sets were selected, on the basis of judgement, to represent five potential "Futures." Each set is of increased capability and technology level with respect to that previous. The sets range from a baseline "do-nothing" technology level representing today's conditions to the "limiting-case" situation which represents ideal conditions for every design parameter and probably would not be ever realized in practice. The baseline case is not shown since its delay levels went off scale. The curve labeled LAX "Today's Spacing (no-wake turbulence)" assumed levels of ground deceleration rates consistent with current operation. It also assumed 3-mile air-to-air separation standards between aircraft on final approach. In addition, low runway turnoff velocities were assumed. Taken as a combination, the results indicate that in today's operations under IFR conditions, the average busy-hour delay would be on the order of 28 minutes. The curve also shows that under the impact of additional traffic, such delay would grow exponentially climbing off the scale by, say, 1985. If technology improvements are made to the airplane and to the air traffic control system, such that reduced aircraft separation distances can be safely achieved; and, in conjunction with this, increased deceleration rates and increased turnoff velocities can be achieved on the ground, then a major jump can be made in terms of reducing average busy-hour delay (see curve labeled "Future 1"). The figure shows, for example, that by 1980 an airspace/airplane system endowed with these advanced capabilities could reduce delay down to on the order of 10 min. Similarly, even more advanced projections of aircraft separation and runway operations parameters could eventually reduce delay levels down below the six-min delay goal. This goal has been set (for the purpose of the study) to be consistent with reports and analyses conducted by the Department of Transportation.

DEFINITION OF CASES CONSIDERED

Assumed technology level	Runway exit speed, kn	Number of exits	Arrival accuracy standard deviation, sec	Separation rule	
				Arrivals, miles	Departures
Today (do-nothing)	0	4	18	5 & 3	1 min
Today, no wake turbulence constraint	0	4	18	3	1 min
Future 1	30	6	12	2.5	6000 ft (along runway)
Future 2	30	6	6	2	Runway occupancy (only 1 airplane on runway)
Limit	60	Continuous	2	Runway occupancy	Runway occupancy

COMPUTER SIMULATION RESULTS

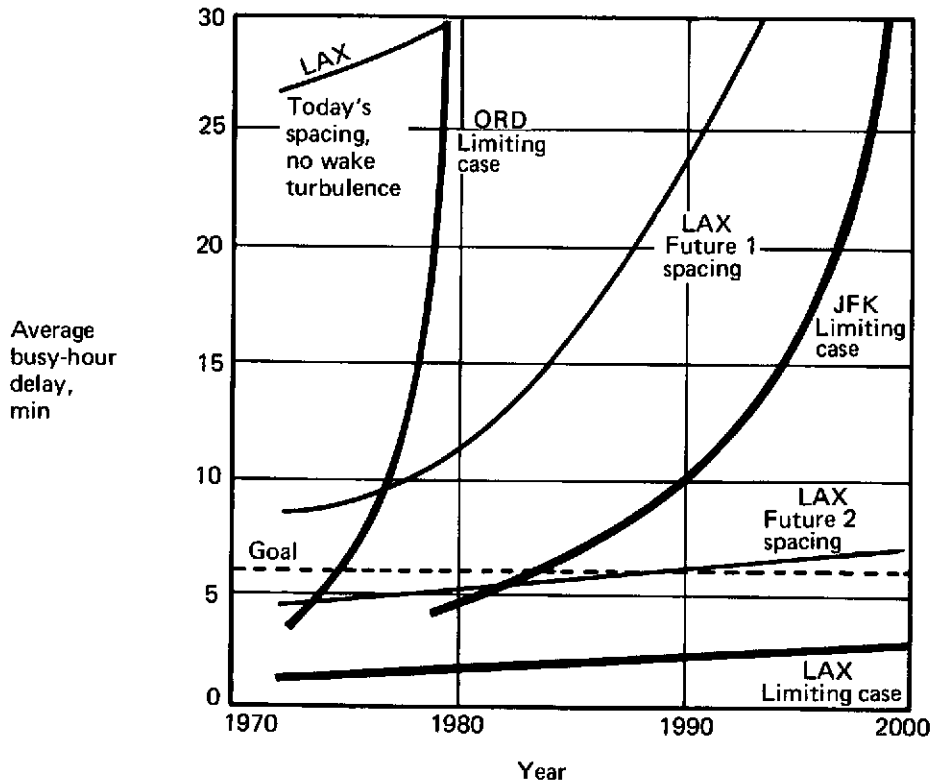


FIGURE 11.—BUSY-HOUR DELAY

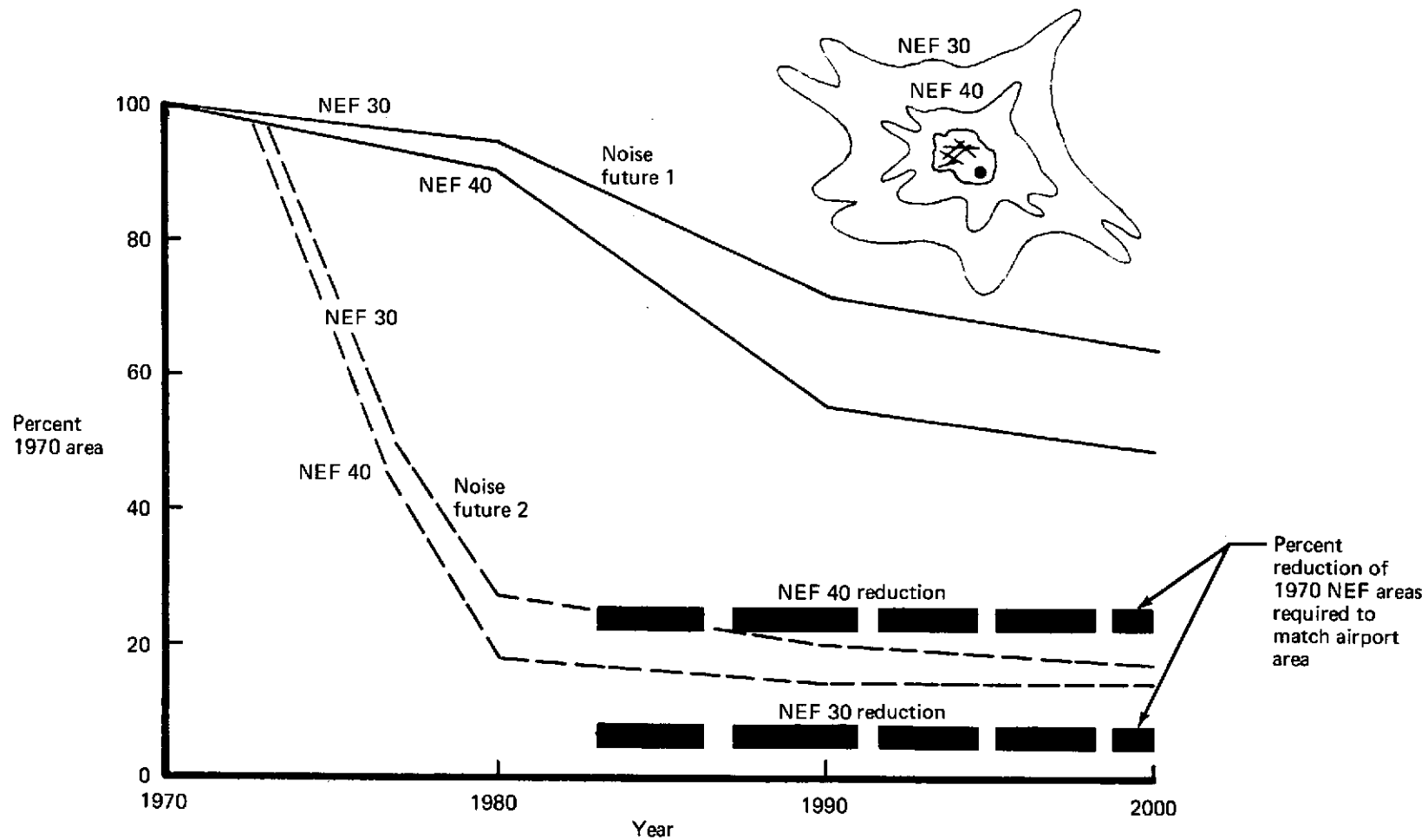


FIGURE 12.—RELATIVE CHANGE IN NEF AREAS VS YEAR FOR A TYPICAL AIRPORT

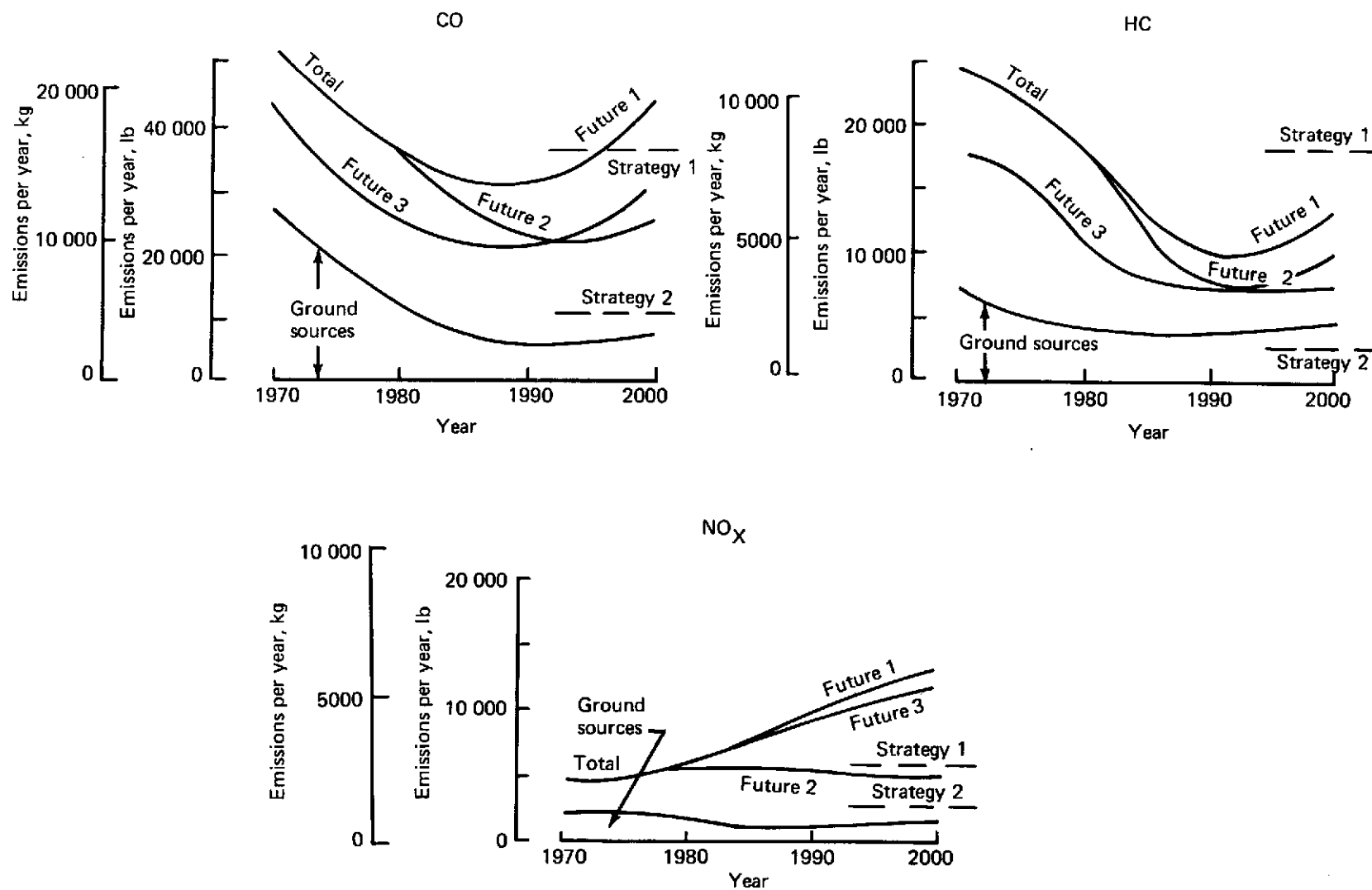


FIGURE 13.—EMISSIONS IMPACT RESULTS—TYPICAL AIRPORT

The reader must keep in mind that in order to achieve the six-min delay goal, the relatively large technology advances associated with the future 2 projections, and/or the limiting case projections, would have to be achieved.

The above discussion was based upon projections for LAX airport. Also shown on the curve is the fact that even for the "limiting case" technology assumptions, delay levels at both JFK and O'Hare would far exceed the goal of six min and in fact reach levels which would be intolerable.

5.2.1 Noise

The impact of air traffic growth on airport noise was similarly projected to the year 2000. This was assessed in terms of noise exposure forecast (NEF) levels which take into account the aircraft fleet mix operating at an airport; the noise characteristics of the different aircraft in EPNdB; the takeoff and landing flightpaths; and the number of total aircraft operations that take place during the day and night.

Figure 12 shows that if nothing were done, i.e., "Noise future 1," the area enclosed by the NEF 30 and NEF 40 noise levels would still decrease by 15% to 20% by 1990 and by 30% to 50% by the year 2000. This decrease would occur assuming current aircraft noisier than FAR Part 36 would phase out and by assuming all advanced-aircraft additions to the fleet would comply with FAR Part 36 requirements. Specifically the noise future 1 fleet assumes: (1) no noise modifications to existing aircraft; (2) existing aircraft fleet lifetimes consistent with historical trends; and, (3) sufficient introduction of advanced FAR Part 36 aircraft to satisfy traffic demand.

In addition, figure 12 shows that a noise future 2 fleet mix could reduce the area enclosed by NEF 30 and NEF 40 noise contours by 80% to 85% by 1990 and through the year 2000. Noise future 2 assumes that adequate funding is provided such that: (1) existing aircraft would be retrofitted to improve their noise characteristics; (2) such retrofit would not alter their fleet lifetime as predicted by historical trends; and (3) sufficient advanced aircraft at noise levels of about 10 EPNdB below FAR Part 36 would be introduced to satisfy traffic demand.

As an aid to interpreting the significance of the percentage reduction in NEF areas shown in figure 12, the heavy dashed lines have been added. These lines give the approximate reduction relative to the 1970 levels, which would be required to match the geometric area of the typical major urban airport. Thus, it is seen that the future 2 level of noise reduction is such that: (1) the NEF 40 area by 1990 would be within the airport boundary; and (2) the NEF 30 area, while not within the airport boundary, would have made significant progress toward that condition.

5.2.2 Emissions

Figure 13 summarizes the predicted tonnage levels into the future for carbon monoxide, hydrocarbons, and oxides of nitrogen. The tonnage levels shown are those deposited in and around the airport area by both ground and aircraft emission sources. These levels are functions of the specific emission levels assumed for both the ground sources and the aircraft. In the case of the aircraft, the tonnage levels are also dependent on the operating times assumed for landing, ground and takeoff operations for the assumed fleet mix of aircraft.

Just as for the congestion and noise studies, three separate emission “futures” were projected. These are distinguished by differing assumptions of the parameters affecting aircraft emissions. The curves labeled “Future 1” in figure 13 represent essentially a “do-nothing” projection. That is, *existing* aircraft are assumed unchanged and all *advanced* aircraft are assumed to have combustors with technology levels equivalent to that of the JT9D/CF6 category of engines. In addition, the landing/takeoff cycle times were defined to be those recently used by the EPA in prescribing aircraft emission standards (total time: 32 min per cycle). These times were based upon data assembled by the Cornell Aeronautical Laboratory based on observed airport operations in and around the years 1968, 1969, and 1970. This time period coincided with a time of considerable airport congestion and in addition encompassed the so-called air traffic controller “slow-down.” Thus, the ground operating times (26 min) used to establish baseline landing/takeoff cycle include considerable ground delay and may be somewhat biased.

The future 2 projections assumed the same ground operating times as assumed for the future 1 case, however, the engine combustor technology for the *advanced* aircraft was assumed to be improved consistent with projections made by the engine manufacturers and by NASA based on advanced combustor concepts. These projections will require considerable R&D expenditure to be realized.

The future 3 case assumes that all *existing* aircraft would retain their current combustors through the remainder of their useful life. Furthermore, *advanced* aircraft would have combustor technology levels consistent with the JT9D. However, it was assumed that ground operating times would be reduced to reflect minimum airport/airplane operating delay.

The results of all projections show a tendency toward decreased CO and HC levels out into the 1990s. This reduction in total emissions is due in large part to an assumed reduction of ground source emissions which are largely attributed to automobiles bringing traffic to and from the airport. Beyond 1990 the increased levels of aircraft traffic begin to catch up with the flattened trend of reduced emissions in ground sources. The situation with NO_x shows a different trend, however; for the do-nothing or future 1 case, a continual increase is shown through the year 2000.

The projections for all three emissions tend to show reduced tonnage levels on the order of 50% provided the advanced combustor technology assumptions of future 2 are realized. In addition, the reduced ground delay assumptions of future 3 will show immediate improvement to the total tonnage levels of carbon monoxide and hydrocarbons on the order of 30% to 50%. The future 3 assumptions do not provide much benefit toward NO_x reductions, however. This is because NO_x is emitted by aircraft engines when operating at high power settings, so that changes to ground operation do not have much leverage on NO_x deposits.

5.3 DESIRABLE AIRPLANE CHARACTERISTICS

Figures 14 through 16 summarize the results of the task II studies in terms of design requirements placed on the terminal-compatible airplane. This summary is presented by delineating terminal area operations into three components: approach-landing operations, ground operations and takeoff operations.

Figure 14 provides a summary assessment of the approach and landing considerations. Assessing the different facets of approach operations, the figure gives an indication of pertinent parameters shown in parentheses as they currently exist at a typical large urban airport. For example, on approach we see separation requirements between aircraft on the order of 5.5 to 9 km (three to five miles), 9 km being required behind large jumbo jets. Total occupancy times on the runway after touchdown are currently on the order of 55 sec. This occupancy time results from ground deceleration levels on the order of 1.8m/sec² (6 ft/sec²) in combination with turnoff velocities which are relatively modest, being between zero and five kn. Typical approach paths are 3 degrees. The approach speeds average about 135 kn. Typical source noise levels for the aircraft are on the order of FAR Part 36 although there is considerable variation, with some of the early turbojet aircraft exceeding these noise levels by 10 to 15 EPNdB. Similarly, "airframe" noise levels (that is, the noise level of the airplane with the engine propulsive noise removed) approached 8 to 12 EPNdB below FAR Part 36. The time inaccuracy associated with the expected aircraft position at a given point in space is on the order of ±18 sec.

In contrast to these values, improved values are shown (without yet saying how the aircraft could achieve these values) which on the basis of the previous airport impact studies would enable the terminal compatibility goals to be achieved under the impact of the forecast traffic growth; at least for certain for the assumed airports.

Thus, for instance, to improve congestion it would be desirable for aircraft to be able to maintain 1.8 to 3.6 km (one to two miles) separation during final approach. If this were achieved, then approach speed reductions to about 120 kn would enable increased operations rates. In

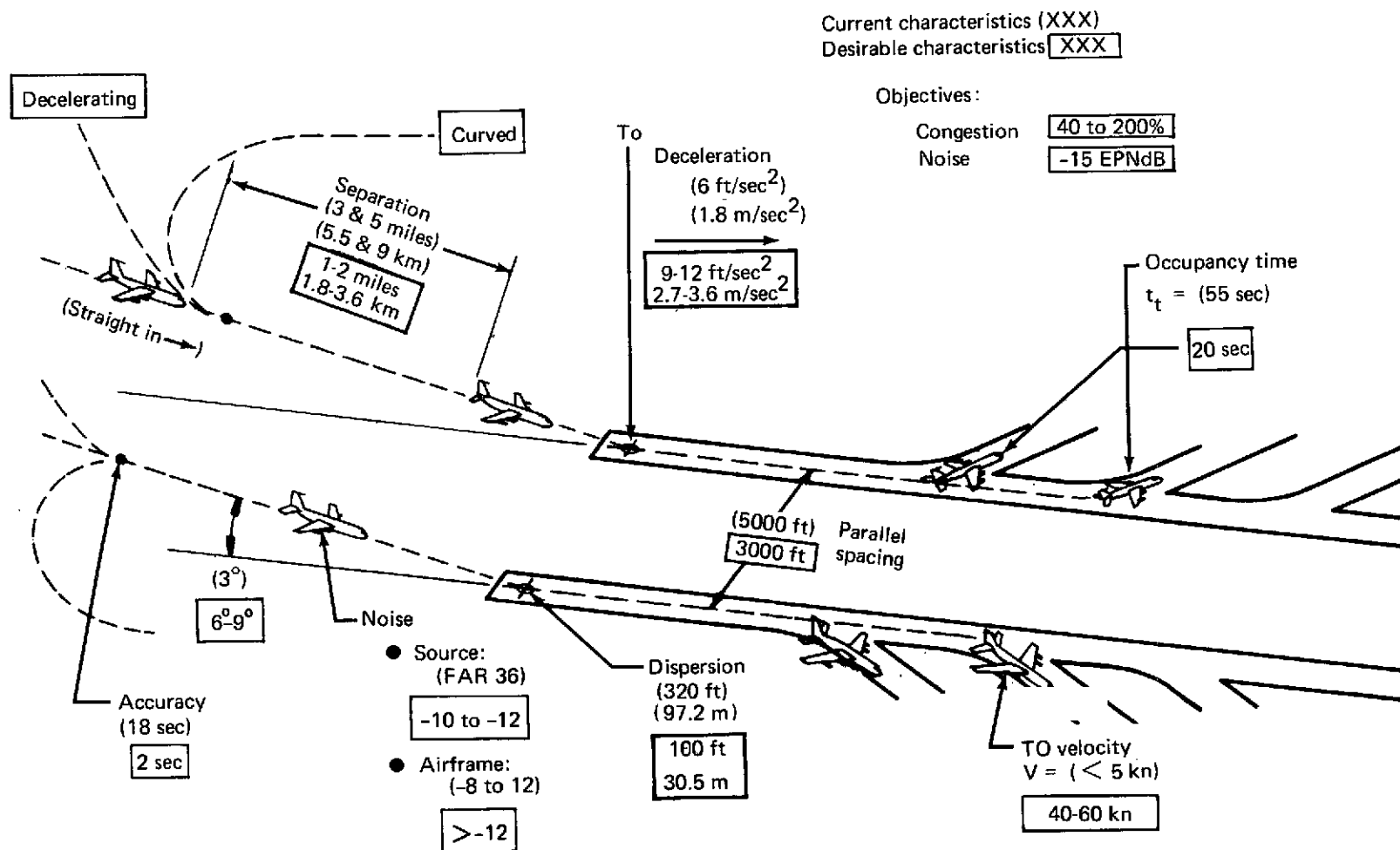


FIGURE 14.—DESIRABLE AIRPLANE CHARACTERISTICS—APPROACH/LANDING OPERATIONS

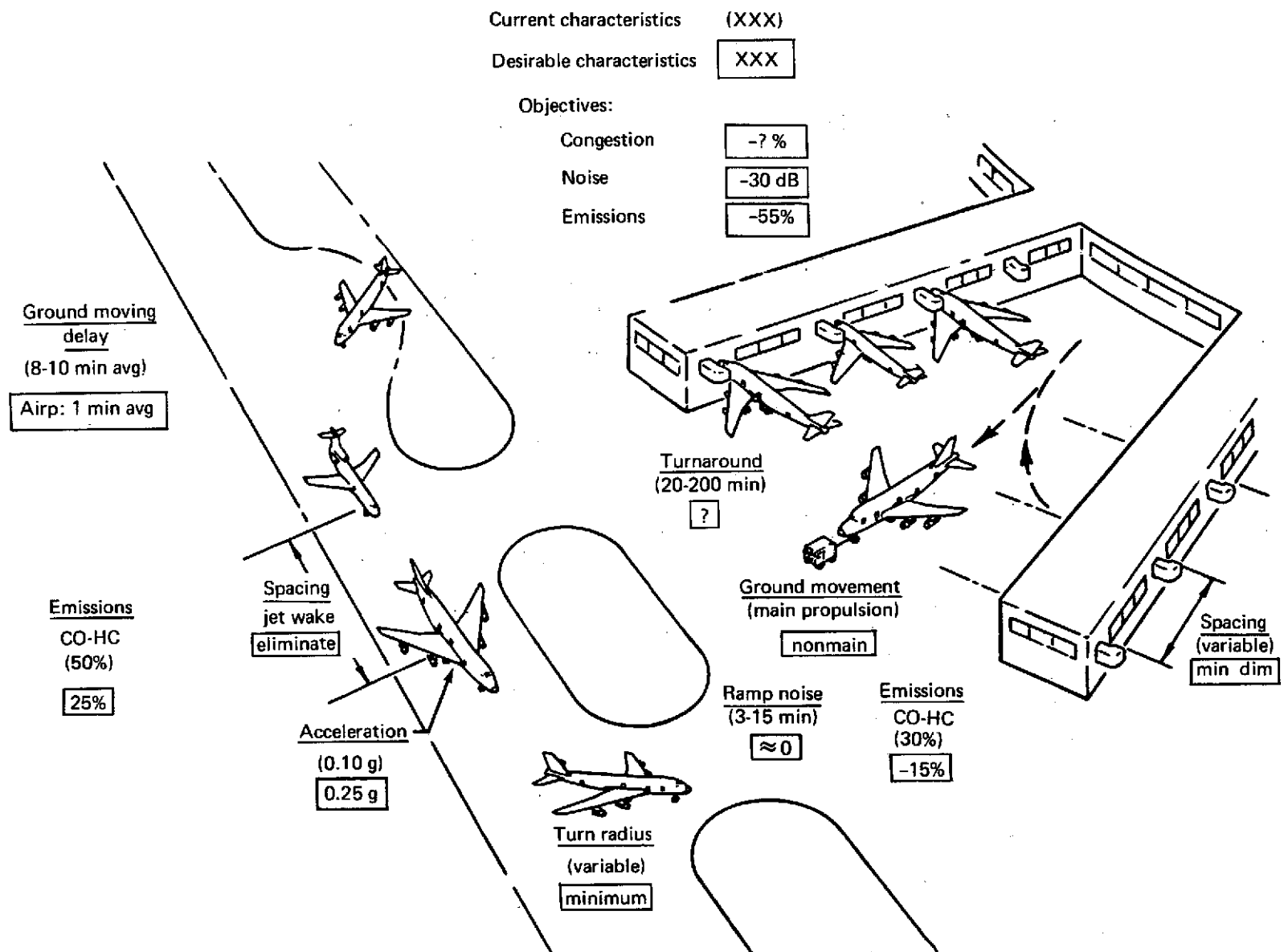


FIGURE 15.—DESIRABLE AIRPLANE CHARACTERISTICS—GROUND OPERATIONS

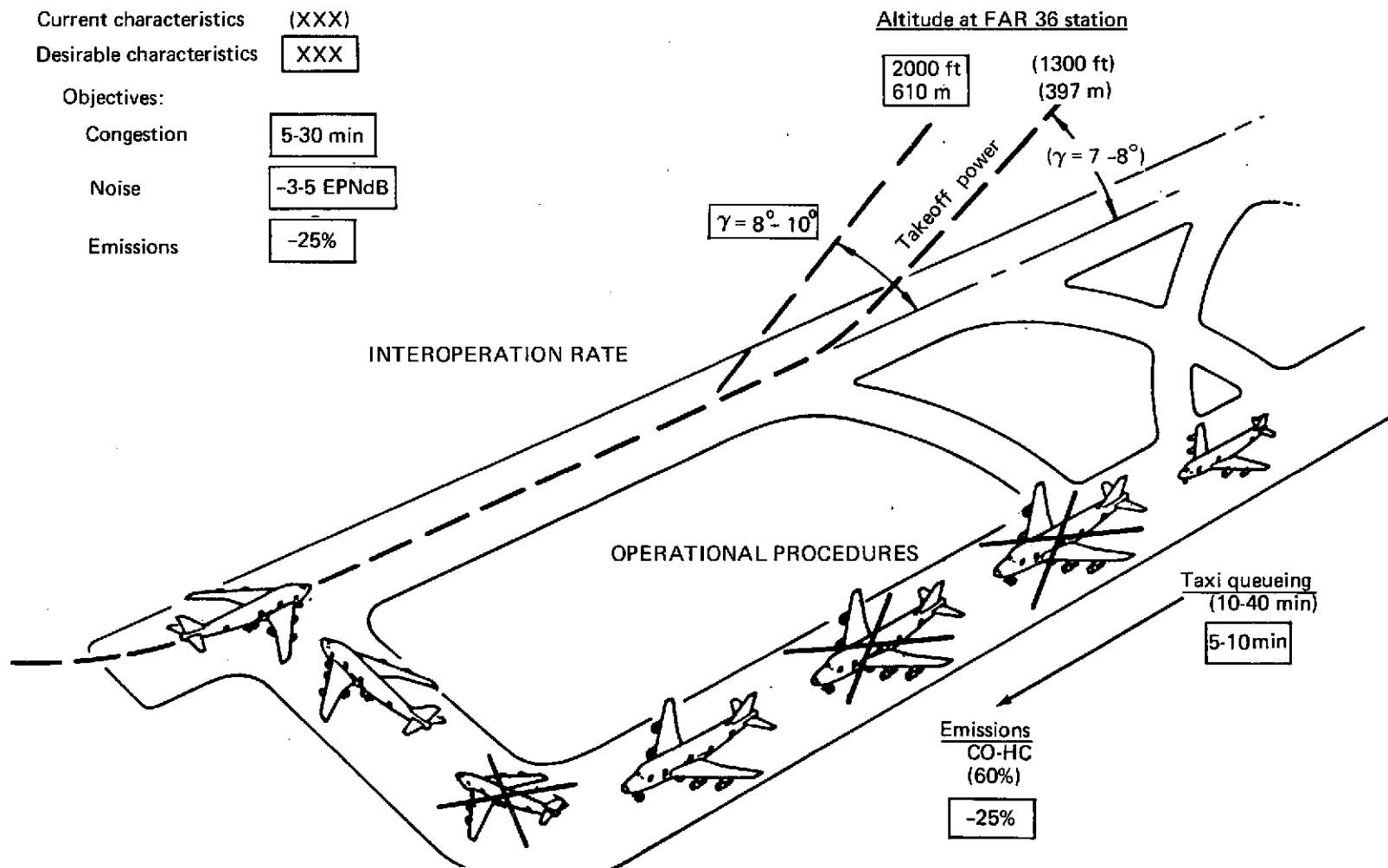


FIGURE 16.—DESIRABLE AIRPLANE CHARACTERISTICS—TAKEOFF/CLIMB OPERATIONS

combination with these improvements, it would be desirable that total runway occupancy times during landing ground roll be reduced to on the order of 20 sec. This would be achieved by increasing deceleration rates on the ground to between 9 to 12 ft/sec² (2.7 to 3.6 m/sec²) in combination with achieving higher turnoff velocities on the order of 40 to 60 kn.

Other desirable characteristics include reduction of airplane source noise levels, increased approach glidepath slopes, and improved knowledge of where the airplane is to reduce, at constant levels of safety, the requirement of 1520 m (5000 ft) spacing for independent parallel runway operations.

Similarly, in reviewing airplane ground operations a number of desirable characteristics were projected. Again, figure 15 illustrates typical current ground operations and also the projections for improved ground operations. Among these improvements was a need for taxi operation of the airplane not utilizing the main engines. This characteristic was deemed desirable largely from the point of view of airplane ground emissions, the concept being that the aircraft would be capable of taxi utilizing direct landing gear wheel drive rather than using the propulsive thrust developed at low power by the main engines. Such a design concept might have additional benefits in terms of improved safety for ground operations by eliminating the hazard of main engine jet blast. This might also improve taxiway operation by reducing the spacing required between lines of taxiing aircraft. In and around the gates, self-powered taxi capability by the airplane might help the aircraft turnaround times by removing the dependence of the airplane on ground tugs in order to back out of the gates.

An additional design feature determined to be desirable on the basis of coordination efforts with various airport personnel was some "invention" enabling reduced gate time and space. Many major airports today are restricted in their capacity to provide gates to the number of operating aircraft.

A similar assessment of takeoff and climb operations is shown in figure 16. In terms of takeoff operations, it was deemed desirable that the airplane be able to achieve steeper climbout angles than current aircraft achieve, as a means of reducing airport noise impact. Current aircraft takeoff climbout gradients are on the order of seven to eight degrees. Based on the task II noise impact studies it was deemed desirable for the terminal-area-compatible airplane to achieve higher climbout gradients, perhaps on the order of 8 degrees to 10 degrees. In addition, it was deemed desirable that the airplane be designed with features that would enable reduction to levels of ground delay. This amounts to recognizing the interplay between ground emissions and airport delay. The latter either occurs on approach in terms of a holding pattern or on the ground prior to takeoff in the form of long queueing lines. These two manifestations of delay are not independent and combine to add considerably to the total level of emissions produced by the airplane in and around the airport environment.

5.4 TASK II CONCLUSIONS

On the basis of the coordination efforts, the airport impact studies and the integrated studies conducted during task II, a number of desirable airplane characteristics were identified which would contribute to advanced airplane compatibility with airplane terminals. It was not possible to quantify all of these. Nevertheless, the total scope of these characteristics are given in table 2.

More specific conclusions derived from this task are:

5.4.1 Congestion

- a) Significant levels of delay and congestion are forecast if nothing is done—study may be biased by use of major airports.
- b) Congestion relief can be achieved by increased runway operations. This will call for aircraft modifications to:
 - 1) Reduce wake-turbulence hazard
 - 2) Slightly lower approach speed
 - 3) Increase aircraft spatial location accuracy
 - 4) Increase deceleration rates and turnoff speeds
 - 5) Reduce parallel runway spacing requirements
- c) Unresolved questions concerning above approach will include
 - 1) Disposition of high-speed aircraft on taxiways after turnoff.
 - 2) Providing gate space and people/baggage/auto throughput for increased aircraft operations
 - 3) Safety and passenger acceptance
- d) Weather plays important role in today's system delays. An all-weather airplane will be highly desirable for an advanced, highly controlled airspace.

TABLE 2.—DESIRABLE AIRPLANE CHARACTERISTICS SUMMARY

CONGESTION

- Greater payload
- Increased low-speed aerodynamic capability
- Control of wing tip vortex
- Improved aircraft positional guidance capability
- Oversized engines for takeoff accelerations
- Improved thrust reversers/brakes for ground deceleration
- Landing gear designed for high-speed turnoffs
- Category III operating capability/collision avoidance systems
- Engine diagnostic aids for reliability evaluation
- Improved aircraft systems design for maintenance
- "Aircraft-carrier" technology for reduced gate space

NOISE

- Improved low-speed aerodynamics— $C_{L_{max}}$, L/D, T/W, W/S
- Auxiliary drag devices
- Lower flight idle engine settings
- Aerodynamic fairings—reduced approach speed
- Quiet fan technology
- Improved acoustic attenuation systems
- Engine placement for noise shielding
- Increased payload-to-gross weight ratio
- Avionics enabling noise-abatement approaches
- Curved approach and takeoff path capability
- Reduced use of main engines for ramp operation

EMISSIONS

- Non-main-engine power for ramp/taxi operation
- Improved combustor design
- Advanced, cleaner fuel systems
- Improved SFC for low-speed operation
- Use of engine aides for maintaining high efficiency
- Increased aircraft payload-to-gross weight ratio

- e) Current built-in delays make the best of a bad situation but amount to system inefficiency
- f) Alternate but unstudied solutions include more airports/schedule restrictions/bigger airplanes/more point-to-point service. These solutions will be required at some airports in addition to aircraft modifications.

5.4.2 Noise

- a) Some noise relief is in sight by simply complying with FAR Part 36 and acknowledging increased use of existing widebody aircraft.

- b) Advanced aircraft fleet at FAR Part 36-10 EPNdB (including modification to current aircraft will reduce NEF areas by 80% using standard operational flightpaths. This assumes increased R&D efforts and some operating cost penalty.
- c) Opportunities for further or alternative noise reduction exist by using improved flightpaths due to:
 - 1) Aerodynamic design of aircraft
 - 2) Use of different procedures.

5.4.3 Emissions

- a) Projected airport pollution levels will show improvement as automobile emission controls become more widespread.
- b) Engine technology trends are favorable to CO/HC reduction, unfavorable to NO_x improvement.
- c) State-of-art technology prevents establishing valid engine emission requirements based on air quality.
- d) Tonnage reductions of CO/HC can be achieved by
 - 1) Less airplane ground time
 - 2) More efficient main engine low-power ground operation
 - 3) Combustor redesign.
- e) Tonnage reductions of NO_x appear to be primarily dependent upon engine modifications such as:
 - 1) Combustor redesign
 - 2) Water injection.

Continued efforts are required to achieve these at acceptable costs.

6.0 TASK III—AIRCRAFT CONFIGURATION DEFINITION

The objective of task III was to refine the broad and specific airplane characteristics identified during task II into a feasible airplane design. To help understand the implications of "terminal-compatible" design, four separate airplanes were configured in this study. The primary features of each of these is shown schematically in table 3 along with the basic motivation for developing each airplane. The various airplanes are briefly described in the introductory section of this chapter. A detailed assessment of the airplanes configured in task III is given in section 7.0 which presents the total performance and economic analysis.

6.1 INTRODUCTION TO STUDY AIRPLANES

Airplane 1, designated CWB (current widebody), was designed to serve as an anchor point representative of today's widebody jumbo jets. The airplane cruise Mach number of 0.85 is typical of today's widebody cruise performance. Furthermore, like existing aircraft, it is devoid of many of the advanced technology features evaluated at length in the previous advanced transport technology programs.

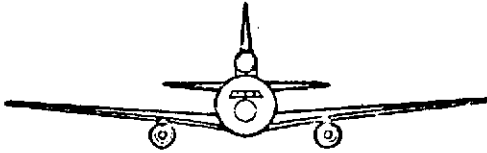
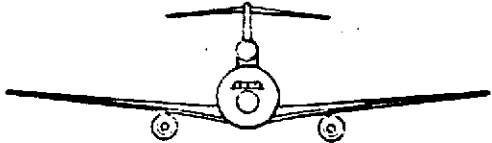
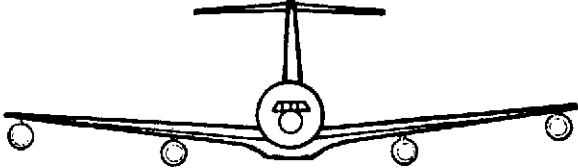
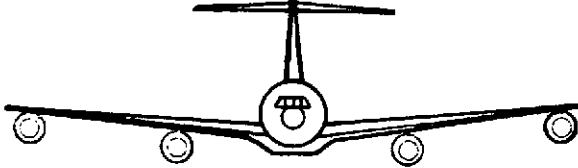
Airplane 2, designated the ATT (Advanced Transport Technology) airplane, was developed under the prior NASA contract (ref. 1). It incorporates significant technology advancement beyond today's widebodied jets. These advancements include: extensive use of composite materials for weight reduction; active controls technology for weight and drag reduction; supercritical airfoil technology; advanced acoustic linings; and improved engine thrust-to-weight levels. This airplane, designed primarily for improved cruise performance, was used as a baseline for the current study.

The third airplane designated TAC (terminal-area-compatible) airplane represented a culmination of all of the studies for the current contract and resulted from direct design modifications to the ATT airplane applied to provide improved airplane/airport terminal compatibility.

The fourth airplane designated TAC-RTOL (reduced takeoff and landing) explored the impact associated with reducing the required field length from 2530 m (8300 ft) to 1520 m (5000 ft). This additional capability was imposed while requiring that none of the terminal-compatible features of the third airplane be sacrificed.

The procedure used in task III for developing the TAC and TAC-RTOL airplanes consisted of several steps which are described briefly below:

TABLE 3.—STUDY AIRPLANE NOMENCLATURE AND PURPOSE

Airplane	Airplane acronym	Reason for configuration development
	<p>CWB</p> <p>(current widebody)</p>	<p>Serves as technology and economic baseline representative of today's widebody jet transports</p>
	<p>ATT</p> <p>(advanced transport technology)</p>	<p>Serves as technology and economic baseline representative of projected 1985 technology with design based principally on efficient cruise capability</p>
	<p>TAC</p> <p>(terminal-area compatible)</p>	<p>Serves to identify and assess design changes desirable for improved airplane/airport compatibility</p>
	<p>TAC-RTOL</p> <p>(terminal-area compatible—reduced takeoff and landing)</p>	<p>Serves to identify airplane impact for 5000-ft runway capability (TAC airplane configured for 2530 m (8300 ft))</p>

6.1.1 Step 1

Alternate design concepts capable of satisfying each of the specific design objectives previously identified in task II were evaluated. For example, improvement to takeoff-climb gradient was identified as a desirable noise reduction feature in task II. A study was conducted to review leverage available on improved gradients by changes to wing area, aspect ratio, thrust size, etc., and on the basis of such studies design approaches were selected for each of the design modifications.

6.1.2 Step 2

A preliminary airplane drawing was then developed defining an airplane containing the desired design modifications. This drawing was then analyzed for configuration acceptability in terms of weight and balance, structural soundness, controllability, aerodynamic drag and propulsion characteristics. Simultaneously, in each of these technologies a sensitivity of airplane weight, drag and SFC characteristics to changes in wing and engine size was defined.

6.1.3 Step 3

The airplane design characteristics were then reevaluated in a computerized airplane sizing program. This step resizes the as-drawn, step 2, airplane to provide the required range and payload. Other design requirements are also considered at this time, such as takeoff field length, approach speed, initial cruise altitude capability, noise levels or other parameters of particular interest. Of the matrix of airplanes developed in the computer analysis, one airplane design compatible with the design requirements was selected on the basis of minimum takeoff gross weight. This design is then redrawn so that a final consistent drawing and analytical definition of the airplane characteristics was obtained.

It is important to note that the principal output of the overall study is an identification of desirable research and technology areas which must be pursued. In this spirit and in keeping with the scope of the study, the four airplane designs developed in task III *serve primarily as a tool whereby the appropriate research and technology areas might be identified*. The designs accordingly do not necessarily represent optimum designs.

Tables 4 and 5 present, in general terms, the design objectives and sizing constraints which were utilized to develop the four airplane configurations. Table 4 shows not only the design objectives but also indicates the design technique that was ultimately employed. The design rationale is discussed more completely later in this chapter. Table 5 shows the primary sizing constraints and indicates that the four airplanes were sized for a 18 140 kg (40 000-lb) payload and a design range of 5560 km (3000 nmi). Three of the advanced airplanes were designed for a cruise

TABLE 4.—STUDY AIRPLANE DESIGN OBJECTIVES AND TECHNIQUES SELECTED


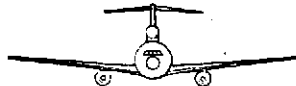
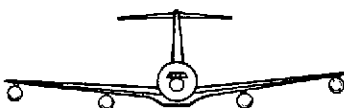
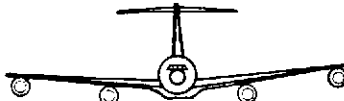




Airplane	Design objective	Design technique
<p>CWB</p> 	Fully represent today's widebody jet aircraft	Use 747/DC-10/L-1011 design and performance data
<p>ATT</p> 	Incorporate technology advances consistent with 1985 certification	<p>Supercritical airfoils</p> <p>Active controls</p> <p>Advanced engine temperatures/materials</p> <p>Improve acoustic lining concepts</p> <p>Advanced composites structures</p>
<p>TAC</p> 	<p>Noise improvement</p> <p>Increased takeoff heights</p> <p>Increased approach gradients</p> <p>Reduced approach power</p> <p>Emission improvement</p> <p>Reduced engine emissions</p> <p>Reduced main engine operation</p> <p>Reduced airplane operation</p> <p>Congestion improvement</p> <p>Reduced air-to-air separation</p> <p>Reduced approach speeds</p> <p>Increased ground deceleration</p> <p>Higher turnoff speeds</p> <p>Improved path accuracy</p>	<p>Higher aspect ratio wing</p> <p>Additional drag devices</p> <p>APU-driven secondary power systems</p> <p>Advanced combustor technology</p> <p>Modified engine cycle</p> <p>Powered wheels for ground taxi</p> <p>Reduced ground delay by congestion relief</p> <p>Wing-tip-mounted engine/blockage devices</p> <p>Higher aspect ratio, increased wing size</p> <p>Higher capacity braking material</p> <p>Improved pilot guidance/steering control</p> <p>Increased avionics equipment capability</p>
<p>TAC-RTOL</p> 	Field length capability of 1520 m (5000 ft)	Increased engine thrust size

TABLE 5.—PRIMARY OPERATIONAL CONSTRAINTS ASSUMED FOR AIRPLANE SIZING




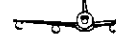
Constraint	 CWB	 ATT	 TAC	 TAC-RTOL
Payload, kg (lb)	18 140 (40 000)	18 140 (40 000)	18 140 (40 000)	18 140 (40 000)
Range, km (nmi)	5560 (3000)	5560 (3000)	5560 (3000)	5560 (3000)
Mach cruise	0.85	0.90	0.90	0.90
Takeoff field length (304.8m/32.2°C), m (1000 ft/90°F), ft	≤ 2530 (8300)	≤ 2530 (8300)	≤ 2530 (8300)	≤ 1520 (5000)
Initial cruise altitude (ISA+ 10°C), m (ft)	≥ 9144 (30 000)	≥ 9144 (30 000)	≥ 9144 (30 000)	≥ 9144 (30 000)
Approach speed, m/s (kn)	≤ 69.5 (135)	≤ 69.5 (135)	≤ 61.8 (120)	≤ 61.8 (120)

Mach number of 0.9, however, the current widebody airplane was defined for Mach 0.85. Maximum takeoff field length and initial cruise altitude capability constraints were essentially constant between the four airplanes except that the TAC-RTOL airplane was designed for 5000-ft runways. In addition, both the TAC and TAC-RTOL aircraft were constrained to reduced approach speeds under the impetus of improved congestion characteristics as will be explained later.

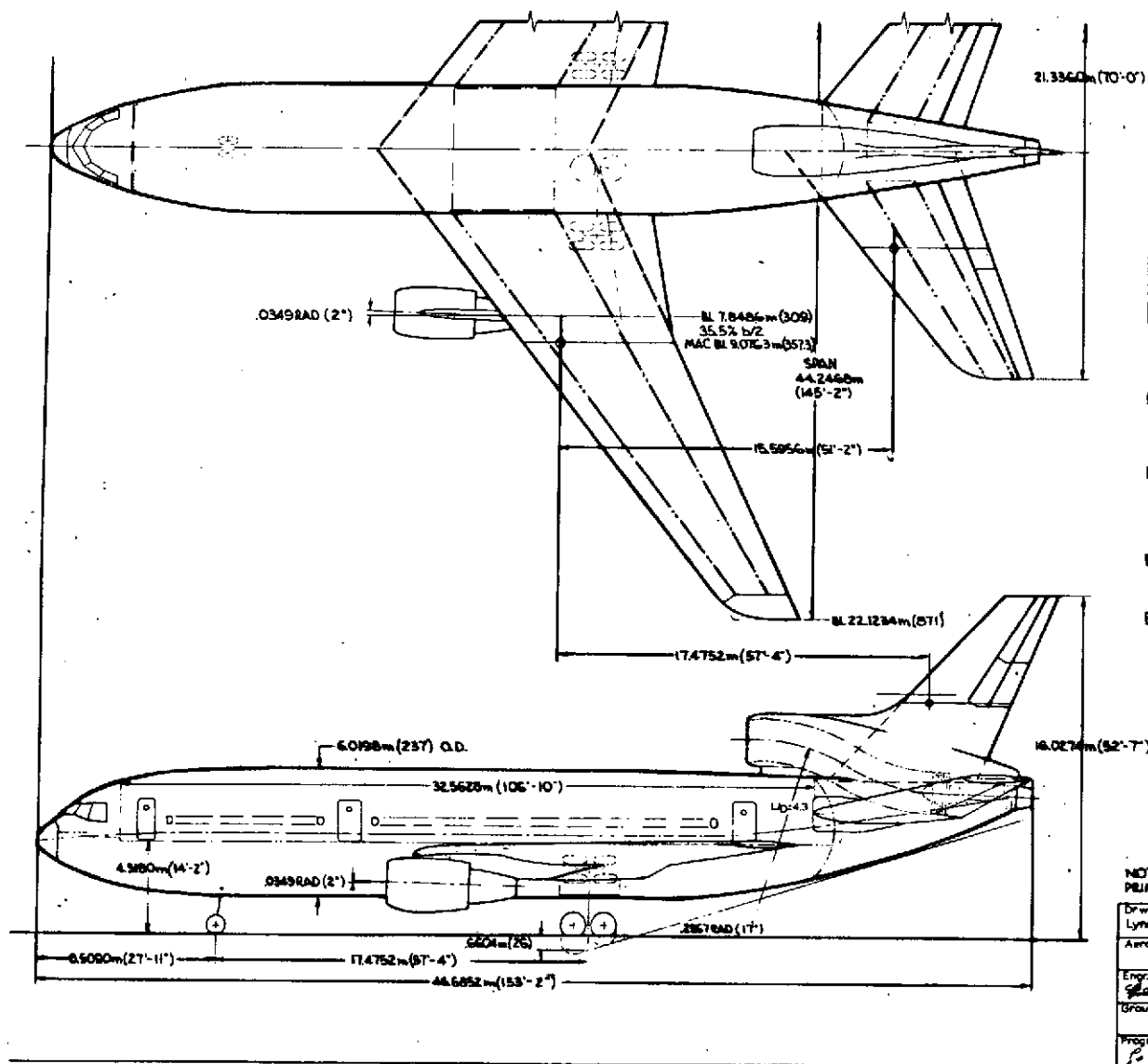
Figures 17 through 20 show the design configurations which were developed for the four study airplanes. As shown in figure 17, the CWB airplane was configured as a three-engine (two-on-the-wing-one-S-duct-aft-mounted) configuration and incorporates a widebody, two-aisle, eight-abreast-seating fuselage. This arrangement led to somewhat shorter fuselage than the three additional airplanes which were configured for double-aisle, seven-abreast seating only. As seen from the figures, the ATT aircraft had the same general arrangement as the CWB airplane with the exception of the smaller fuselage diameter. For reasons which will be explained subsequently in this chapter, both the TAC and TAC-RTOL airplanes utilize four-engine-on-the-wing configurations which serves to distinguish them somewhat from the first two aircraft. It may also be noticed (again for reasons that will be discussed later) that the outboard, wing-mounted engines for the latter two aircraft are positioned at relatively far outboard spanwise locations.

Table 6 presents summary characteristics of the four study airplanes based on the results of the task III efforts. The data are presented here in order to orient the reader more fully toward the subsequent discussion of the four airplanes in the rest of this chapter and further in section 7.0.

TABLE 6.—STUDY AIRPLANES—SUMMARY CHARACTERISTICS^a

Characteristic	 CWB	 ATT	 TAC	 TAC-RTOL
M _{cruise}	0.85	0.90	0.90	0.90
TOGW, kg(lb)	152 400 (336 000)	137 100 (302 200)	141 100 (311 100)	149 700 (330 000)
OEW, kg(lb)	88 000 (194 000)	72 210 (159 200)	78 310 (172 630)	84 050 (185 290)
Wing area, m ² (ft ²)	288 (3100)	214 (2300)	239 (2570)	253 (2720)
Sweep, rad (deg)	0.611 (35.0)	0.637 (36.5)	0.637 (36.5)	0.637 (36.5)
Aspect ratio	6.8	7.6	9.0	9.0
Engine/number	CF6-6D/3	ATSA4/3	ATSA4/4	ATSA4/4
Thrust per engine, sea level	148 100 (33 300)	138 300 (31 100)	103 200(23 200)	125 900 (28 300)
Static, N(lb)				
Acoustic treatment	Peripheral	2R/1S	2R/1S	2R/1S
TOFL, m (ft)	2530 (8300)	2530 (8300)	2530 (8300)	1520 (5000)
Approach speed, m/s (kn)	62.8 (122)	69.5 (135)	61.8 (120)	61.8 (120)

^a5560 km (3000 nmi) range; 18 140 kg (40 000 lb) payload



AREA	m ²	WING	VERTICAL STABILIZER	HORIZONTAL STABILIZER
SOFT		287.9934	212.253	126.167
ASPECT RATIO		3.00	4.00	7.93
WING RATIO		5.8	1.56	3.75
SWEEP C4	RAD	6.09	6.951	6.09
INCIDENCE	RAD	0.73	40	35
CHORDAL	DEG	0.73	---	---
CHORDAL	RAD	12.47	---	17.45
ROOT LE	DEG	9	---	---
TIP LC	%	12	10	10
ROOT CHORD	m	100.76	6.9550	8.0515
TIP CHORD	m	2.9512	2.2432	3.2258
MAC	IN	118	98	71
SPAN	IN	71.94	508.00	5.9580
SPAN	IN	29	200	235
TAIL ARM	IN	44.2245	8.6135	21.3360
TAIL ARM	IN	1742	347	840
TAIL VOL COEF		---	17.4752	15.9956
		---	0.60	0.14

GROSS WEIGHT - 1494 602 N (336000 LB)

PROPULSION SYSTEM

(3) CF 6-6 TYPE ENGINES
M7970N (33265LB) TSLs
BY-PASS RATIO = 6.0:1

LANDING GEAR

	MOSE QUAL	MAIN TRUCK
TYPE		
SPACING	5096m (24)	864m x 122m (34x56)
TIRE SIZE	940m x 35cm (37x14)	1168m x 106m (46x16)

BODY CROSS SECTION

CIRCULAR
60190m DIAMETER (237)

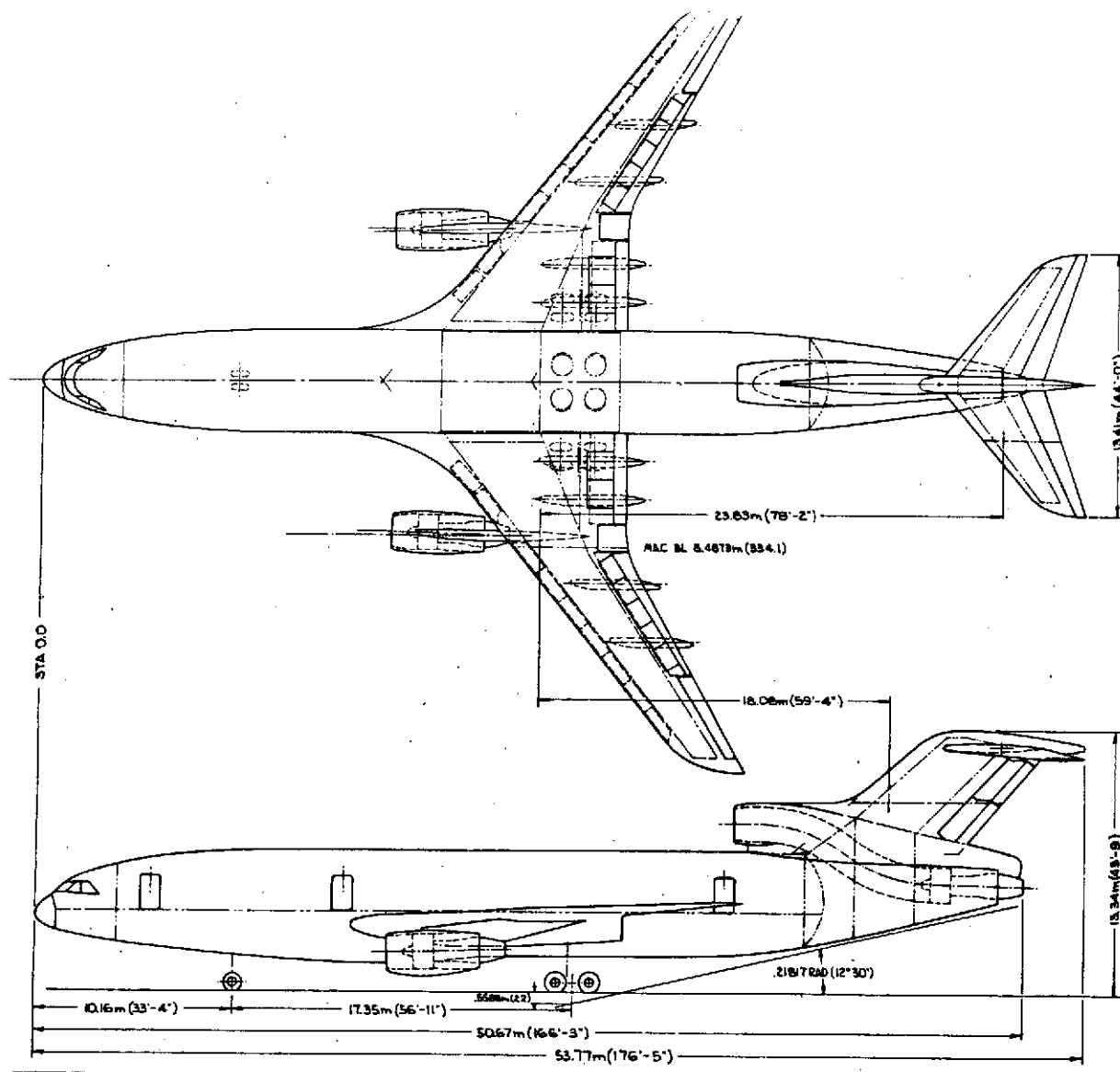
PASSENGER ACCOMMODATIONS

105 PASSENGERS

NOTE: CUSTOMARY UNITS WERE USED FOR
PRINCIPAL MEASUREMENTS AND CALCULATIONS

Drawn By Lynn Johnson	THE BECKING COMPANY CORPORATE OFFICE SEATTLE, WASHINGTON 98101
Aero 8-3	GENERAL ARRANGEMENT - DRWG. Model 787-641 CWB
Eng. 6-3	
Group	
Program <i>So. 1000 (11/17)</i>	Scale: 1/100 Orig. No. 65-8966

FIGURE 17.—GENERAL ARRANGEMENT—CWB



	WING	VERTICAL STABILIZER	HORIZONTAL STABILIZER
AREA m ²	209.5609	41.7430	23.6555
ASPECT RATIO	2.250	4.44	5.57
WING RATIO	1.6	1.6	1.6
SWEEP 1/4 RAD	35.0	82.90	60.9
INCIDENCE RAD	36.5	27.5	25
DEG	0.636	1.1	1.1
DHEDRAL RAD	11.45/0524	1.1	0.873
DEG	10/3	1.1	5
ROOT LE	11.508	1.1	1.1
TIP LE	10.4	1.1	1.1
ROOT CHORD m	7.6200	8.5344	5.5394
IN	300	335	211
TIP CHORD m	2.8356	6.3326	2.0526
IN	114	269	82
MAC m	5.6134	7.7216	3.5624
IN	221	304	140
SPAN m	33.95	5.3645	13.112
IN	1372	211.2	528
TAIL ARM m	18.08	1.1	1.1
IN	712	44	44
TAIL VOL COEF	1.01	0.85	1.01

GROSS WEIGHT: 1344282 N (302200 LB)

PROPULSION SYSTEM

(3) ATSA-4-2800-24 ENGINES
RATED AT 139229 N (31300 LB) S.L.S.
BYPASS RATIO = 4:1

LANDING GEAR

NOSE TRUCK
TYPE: DUAL
SPACING: 6.60m (21'-6")
TIRE SIZE: 0.64m x 2.79m (21'-6" x 9'-2")

MAIN TRUCK
TYPE: DUAL
SPACING: 3.40m (11'-2")
TIRE SIZE: 1.18m x 4.06m (38'-10" x 13'-4")

BODY CROSS SECTION

DOUBLE LOBE: 5.2451m (206.5") x 5.1943m (204.5")

CARGO & BAGGAGE VOLUME

CONTAINERS: 36812 m³ (1300 FT³)
BULK: 14.156 (500)
TOTAL m³ (FT³): 50970 (1800)

0 1 2 3 4 5
0 100 200
INCH

NOTE: CUSTOMARY UNITS WERE USED FOR PRINCIPAL MEASUREMENTS AND CALCULATIONS

DESIGN NUMBER		GENERAL ARRANGEMENT	
DATE	REV	GENERAL ARRANGEMENT	
ENGR	65	ATT	
CHKD	65	TGT-6A08	
DESIGN APPROVAL		65-81962	
S. H. Hall		65-81962	
SCALE		1/4" = 1'-0"	

FIGURE 18.—GENERAL ARRANGEMENT—ATT

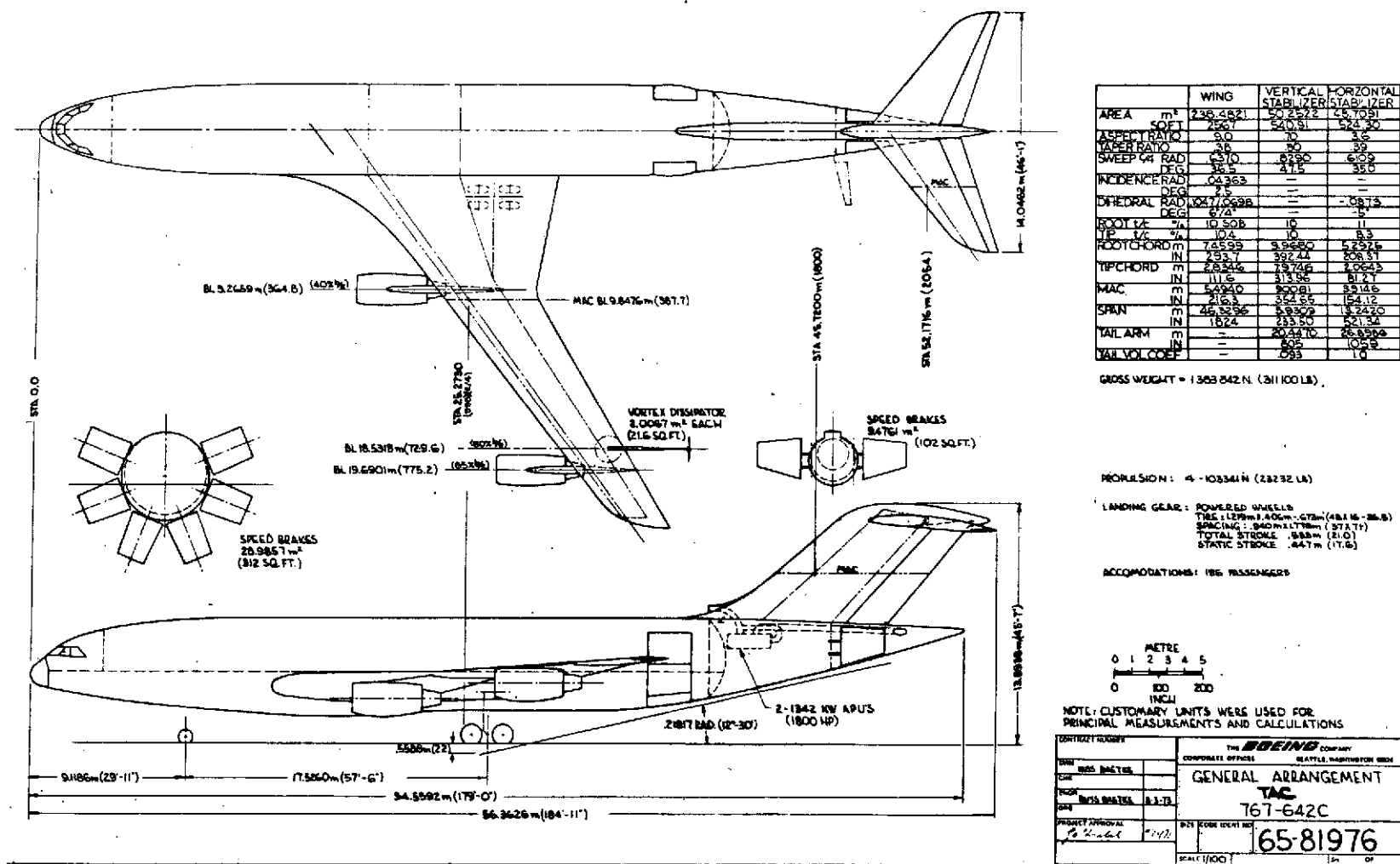


FIGURE 19.—GENERAL ARRANGEMENT—TAC



FIGURE 20.—GENERAL ARRANGEMENT—TAC-RTOL

The figures give a number of “sized” airplane characteristics including a description of the engine and acoustic treatment, such geometric characteristics as wing area, aspect ratio, OEW, etc. Since the four aircraft have all been designed to the same payload/range, TOGW (takeoff gross weight) can be used as a figure of merit to assess the efficiency of the airplane design, bearing in mind the lower cruise speed of the CWB airplane. It is seen that the ATT airplane is on the order of 10% lighter than CWB airplane in spite of its increased cruise speed. This improved efficiency, of course, results from the assumed improvements in structures, propulsion, aerodynamic and acoustic technologies. Relative to the ATT airplane, the TAC airplane incurs a gross weight penalty on the order of 3%. Relative to the TAC airplane, the fourth, TAC-RTOL airplane incurs an additional penalty on the order of 6% to 7% gross weight as a result of the increased engine and tail size which were incorporated to provide 1520-m (5000-ft) field length capability. The basis and reasons for these variations in TOGW are discussed more fully in the remainder of the presentation for task III and also are more clearly explained in the assessment of the four airplanes which are given under the task IV study results.

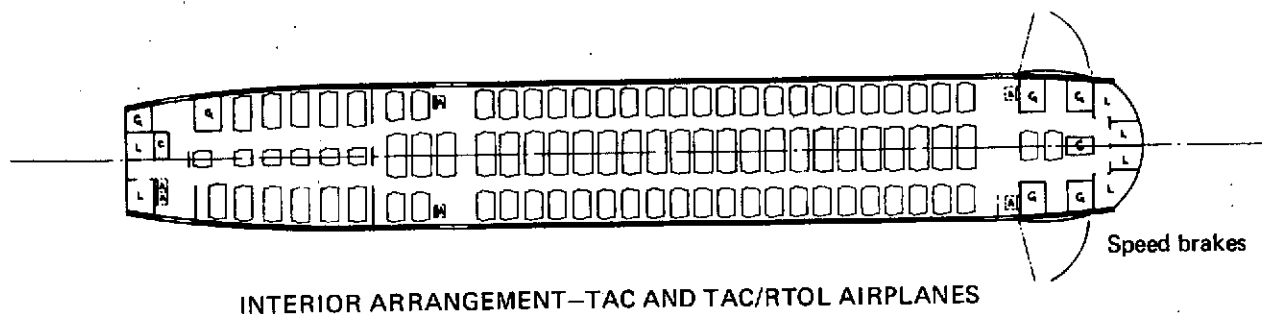
6.2 PRINCIPAL TECHNOLOGY ASSUMPTIONS

This section discusses the basic assumptions used to configure the four study airplanes for each of the preliminary design technologies.

6.2.1 Configurations Technology

Figure 21 illustrates an example of the seating arrangement used to define fuselage lengths and diameters. In addition, the principal configuration ground rules are presented. These ground rules were developed to provide a consistent design framework for configuring a comparable series of aircraft designs.

The passenger payload is arranged with dual aisles and a 15/85 split between first class and tourist passengers. All four airplane passenger compartments contain seats for 196 total passengers plus room for galleys, lavatories, closets, and attendants' stations. The current widebody airplane body used the 6.02-m (237-in.) diameter fuselage configured for eight-abreast seating. Advanced technology airplanes used a smaller 5.24-m (206.5-in.) diameter body with seven-abreast seating. The essential difference between the body diameters is due to the requirements for additional airplane fineness ratio at the higher Mach 0.9 cruise speed. Some rearrangement of the seating design was required for both the TAC and TAC-RTOL airplanes. In this case the seats in the aft end of the airplane and the galleys were rearranged so that no seats would be aft of the fuselage speed-brake assembly necessary for both the TAC and TAC-RTOL airplanes.



INTERIOR ARRANGEMENT—TAC AND TAC/RTOL AIRPLANES

PRINCIPAL CONFIGURATION GROUND RULES

- Aft fuselage upsweep to allow $12^{\circ} 30'$ rotation
- Engine hi-lite to ground ≥ 0.6 engine diameter
- Roll angle at 0° pitch = 11°
- Area plot reasonably smooth
- Airplane fineness ratio > 8.0
- Wing dihedral inboard $\leq 10^{\circ}$; outboard $\leq 5^{\circ}$
- Cab visibility—conventional
- Gear—4-wheel truck
- Seating similar to ATT baseline
- Low wing

FIGURE 21.—CONFIGURATION TECHNOLOGY

Volume was provided below the passenger cabin floor for containerized and bulk cargo, passenger cabin doors, cargo doors, and passenger services designed to be compatible with current airline practice, passenger cabin deck heights compatible with current airport passenger loading facilities. A major airplane geometry constraint was to provide sufficient airplane wing, engine and tail ground clearance.

Attention was given to cg location and balance of the four aircraft. For example, the wing location was shifted aft on the RTOL airplane relative to the TAC airplane to account for the change in balance due to increased engine and tail size. In addition, “gulling” of the wing in some of the aircraft configurations was necessary to obtain body roll angle clearance of up to 11 degrees. A design limit on wing dihedral was adhered to of no greater than 10-degree maximum inboard dihedral or 5-degree maximum outboard dihedral.

The location of the landing gear in the airframe was a critical consideration in development of all configurations. Such parameters as takeoff flare angle, engine clearance, landing load factor,

total main-gear shock strut length are among the most influential design parameters. For the purposes of the present study, landing gear stroke length was set by the requirement that landing load factors be in the neighborhood of 0.9 to 1 which is well within the range of current aircraft design practice. Aircraft flotation characteristics were also considered and constrained in terms of load classification number (LCN) to levels which are no larger than those of current aircraft.

6.2.2 Aerodynamics Technology

The aerodynamic data for the baseline advanced technology (ATT) airplane correspond to that developed under the previous ATT study.

The low-speed data were calculated using established methods for the assumed flap geometrics and were based on available wind tunnel data from similar configurations. The basic flap system consisted of cambered leading edge devices and double-slotted main aft trailing edge flaps. The trailing edge flaps are externally supported with the tracks covered by fairings. These flap systems were selected during the ATT program after study of several candidate systems. The aspects of flap design investigated were: (1) effect on TOGW and OEW for a given mission, (2) price, (3) maintainability and reliability, and (4) producibility. The selected systems appeared to offer the best compromise between the various aspects investigated.

Low-speed drag polars for the airplanes developed under the current study are shown for both takeoff and approach configurations in figure 22. Each of the advanced technology airplanes essentially uses the basic ATT flap system adapted to the specific wing planform. The critical flap geometric characteristics are the same for all the airplanes so that the differences in low-speed performance are due largely to variation in wing aspect ratio.

The low-speed data of the current technology CWB airplane are consistent with available data for existing widebodied airplanes.

The high-speed drag polars of the baseline ATT airplane are the same as those developed previously under the ATT contract. These previous ATT drag levels were developed from NASA Mach 0.98 wind tunnel data corrected to full-scale conditions. Corrections were also incorporated for cruise Mach number and geometry changes together with an 8% friction-drag allowance for roughness and excrescences. The high-speed drag polars for the TAC and TAC-RTOL airplanes were derived from the baseline ATT data accounting for differences in zero-lift drag and the effect of aspect ratio on induced drag. The trim drag of all the advanced technology aircraft was adjusted for changes to average cruise center of gravity allowed by stability augmentation.

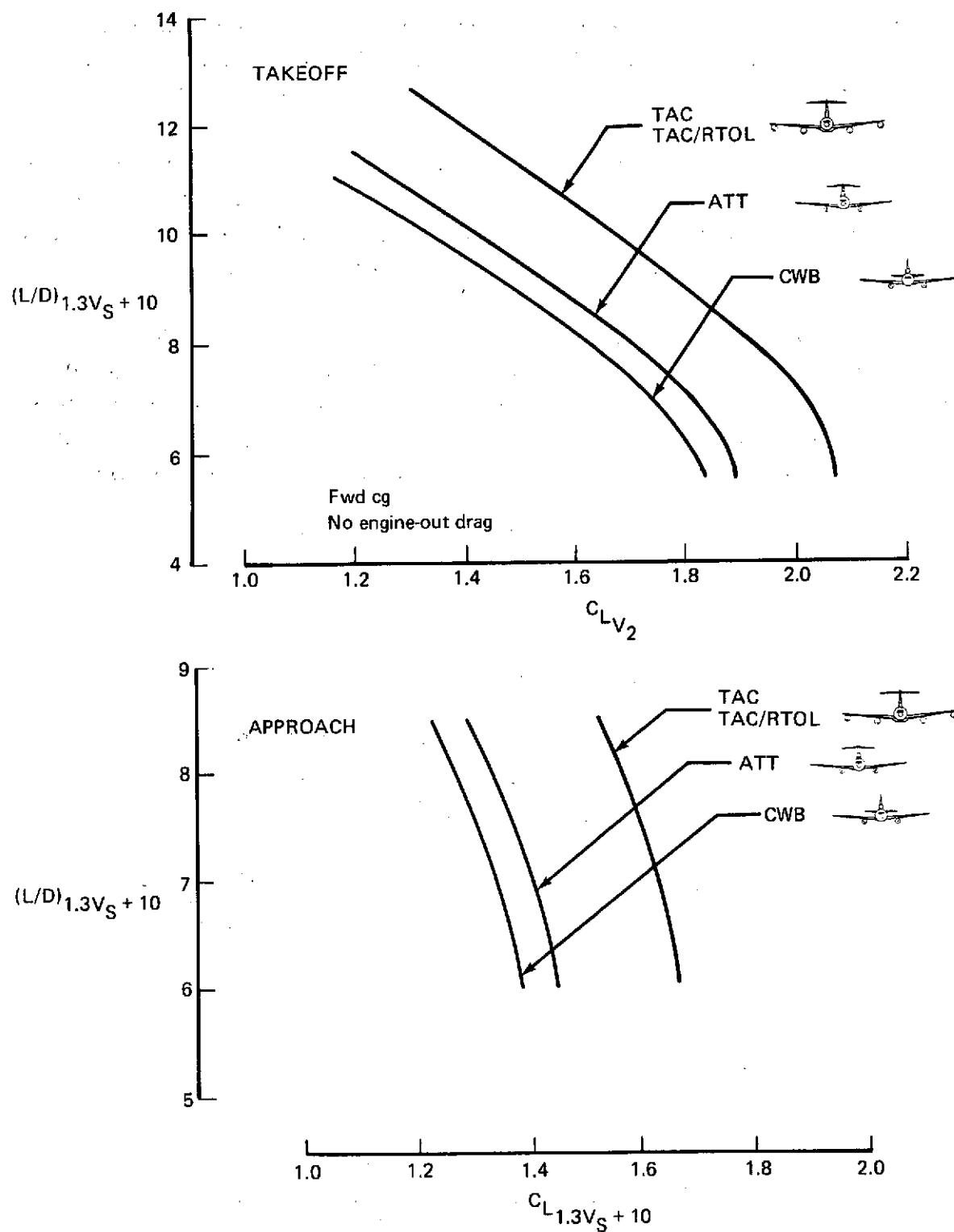


FIGURE 22.—LOW-SPEED AERODYNAMIC CHARACTERISTICS

The drag polars of the conventional technology airplane (CWB) are based on data consistent with current widebodied airplanes such as the DC-10, L-1011 and B-747. A correlation of cruise L/D levels in terms of wing span and total airplane wetted area is shown in figure 23.

The basic airfoil used for the advanced technology designs was the NASA supercritical section. The outboard wing thickness and quarter-chord sweep values for these airplanes were 10.5% and 36.5 degrees, respectively. The inboard thickness variations were selected to meet landing gear and structural requirements. The CWB airplane was configured with a conventional airfoil.

All the advanced technology airplanes had similar wing parameters except for aspect ratio which was increased to 9.0 from 7.6 for the TAC and TAC-RTOL airplanes. The basic Mach 0.9 wing planform was the same as that used in the previous ATT study including a taper ratio of 0.38. This planform was derived from the planform of the Mach 0.98 airplane of the same study holding structural aspect ratio constant. The conventional technology CWB wing had 35-degree sweep, aspect ratio 6.8 and taper ratio equal to 0.30.

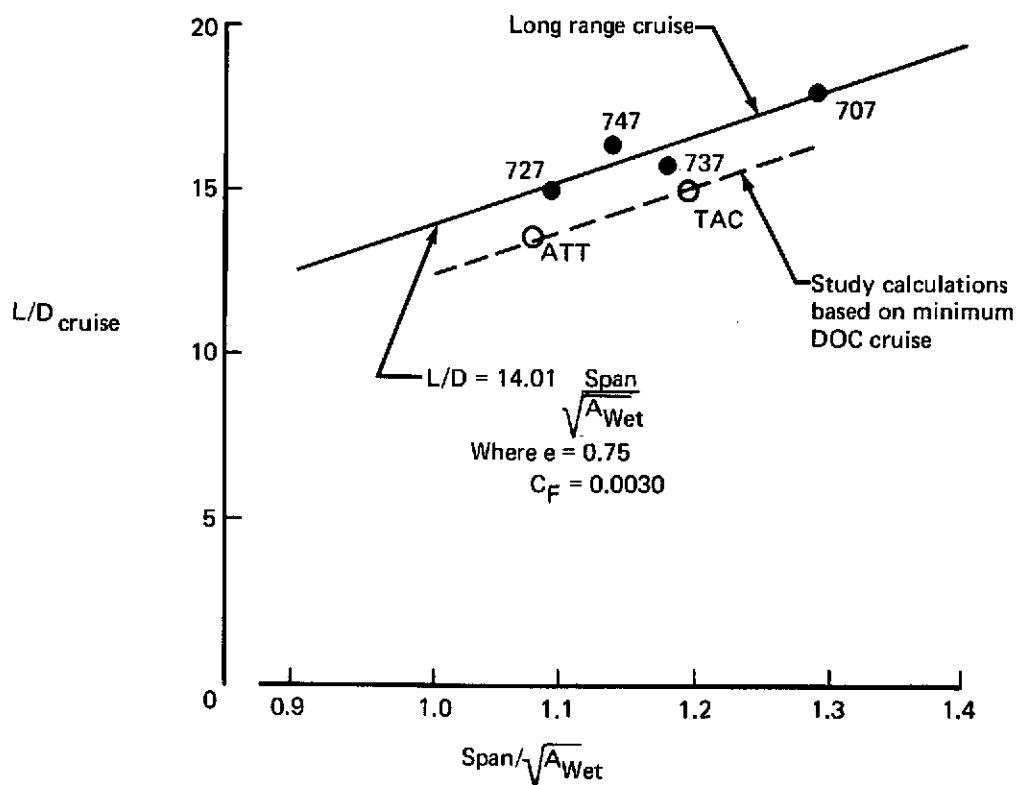


FIGURE 23.—EFFECT OF WETTED AREA AND SPAN ON CRUISE EFFICIENCY

6.2.3 Propulsion Technology

A parametric engine cycle selection study was conducted in the previous ATT study. A Boeing-developed advanced transonic-subsonic (ATSA) parametric engine family was used. The primary assumptions included in the ATSA engine family are: (1) fixed relationship between maximum climb and cruise turbine inlet temperatures, (2) selection of fan pressure ratio for optimum SFC, and (3) one- and two-stage design fan pressure ratio limits of 1.7 and 2.6, respectively.

The current study, based on the results of the previous ATT study, utilizes the ATSA 4-2800-24 [BPR = 4, TIT = 1556° K (2800° R), APR = 24] parametric engine cycle which was determined to be the optimum cycle selection when noise considerations were included. The characteristics of this engine agreed well with the characteristics of similar engines proposed by the engine manufacturers under parallel ATT contracts.

As shown in figure 24, the ATSA engine was installed on all the advanced technology airplanes. The level of noise treatment used was that employed previously for the ATT Mach 0.9 baseline airplane during the ATT study. This noise level, on the order of 10 EPNdB below FAR Part 36 required peripheral acoustic treatment plus two treated inlet rings and one treated fan-duct splitter. The current technology, CWB airplane was configured with the existing General Electric CF6-6D (BPR = 5.9) engine.

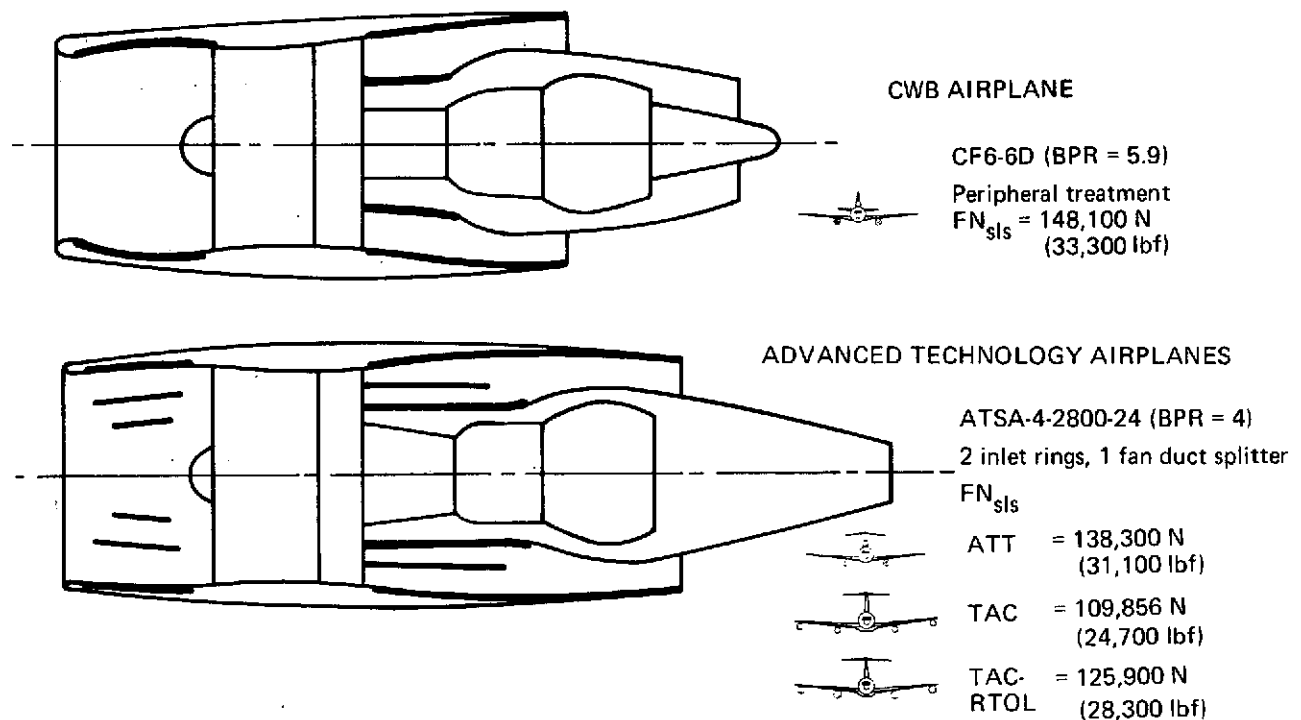


FIGURE 24.—PRINCIPAL PROPULSION SYSTEMS USED ON STUDY AIRPLANES

Installation losses were estimated for both engine installations and included penalties for inlet recovery loss, fan-duct pressure loss, primary and fan-nozzle thrust coefficients, horsepower extraction, bleed air, and scrubbing drag on the core-engine afterbody. In addition, losses associated with internal drag due to the inlet rings and fan duct splitters were estimated. As explained later, the horsepower and bleed-air penalties were modified from standard losses for the TAC airplanes in the case where secondary power systems were driven from the dedicated-in-flight auxiliary power unit (APU).

A summary in terms of cruise thrust per unit airflow and installed SFC is shown in figure 25 for both the CWB, ATT, and TAC airplanes. The figure illustrates the improved thrust per pound of airflow achievable by the ATSA engine due largely to its lower-bypass ratio and two-stage fan configuration. At the same time, these same design parameters degrade the installed SFC of all the advanced technology aircraft (ATSA engines) particularly when losses accounting for acoustic treatment have been considered.

Figure 26 provides information concerning the emission technology levels assumed for both the main propulsion engines and the auxiliary power units for the four airplanes considered in the current study. The figure shows pollutant levels in terms of grams of pollutant per kilogram of fuel burned (pounds of pollution/1000 lb fuel) for carbon monoxide, hydrocarbon, and oxides of nitrogen (the three pollutants considered in the current study). Main engine pollution characteristics for the CWB airplane are based on data available from such current high-bypass ratio engines as the CF-6 and JT9D. Levels shown for the ATT airplane correspond to an average based on the previous engine manufacturer's ATT studies for pollutant levels characteristic of advanced combustion technology.

The data for the TAC and TAC-RTOL airplane represent goals as defined by the current contract Statement of Work. It should be noted that the levels shown are for typical idle power settings for CO and HC whereas the NO_x levels are shown at maximum power. The pollutant levels shown for the auxiliary power units assumed the same APU technology for the CWB and ATT airplanes. Since these APU's were sized simply for ground operation it is assumed that during ground operation these APU units are operating at 100% thrust. In contrast, the TAC and TAC-RTOL had an APU unit sized for in-flight use and consequently are operated at a partial power setting during ground operations. The high level of emission index for carbon monoxide shown in figure 26 for the TAC airplane APU unit represent a part-power effect.

6.2.4 Noise Technology

The noise prediction methods used in the current study are identical with those utilized previously under the study. These procedures involve prediction of engine noise and nacelle

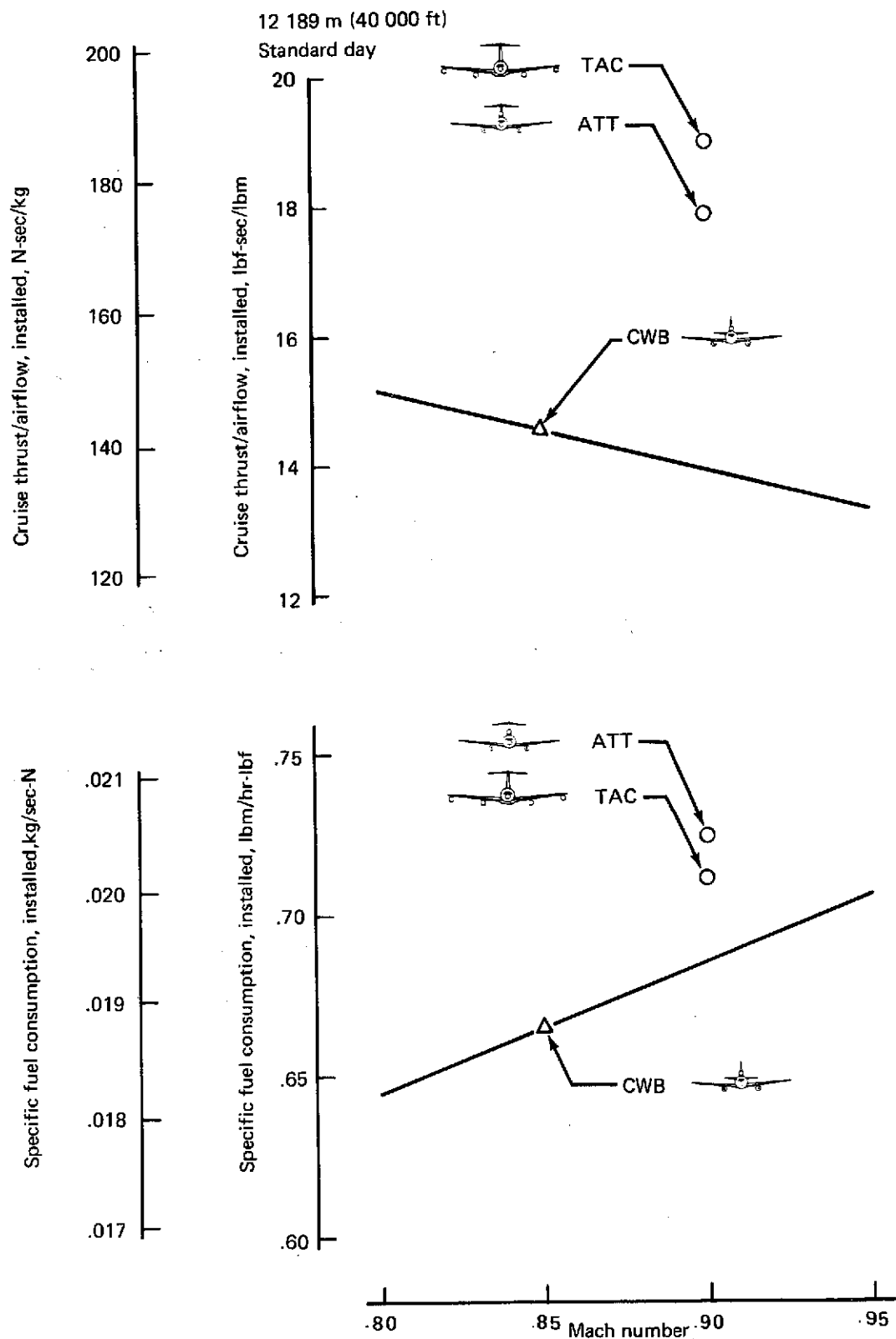


FIGURE 25.—ENGINE INSTALLED PERFORMANCE COMPARISON—CRUISE

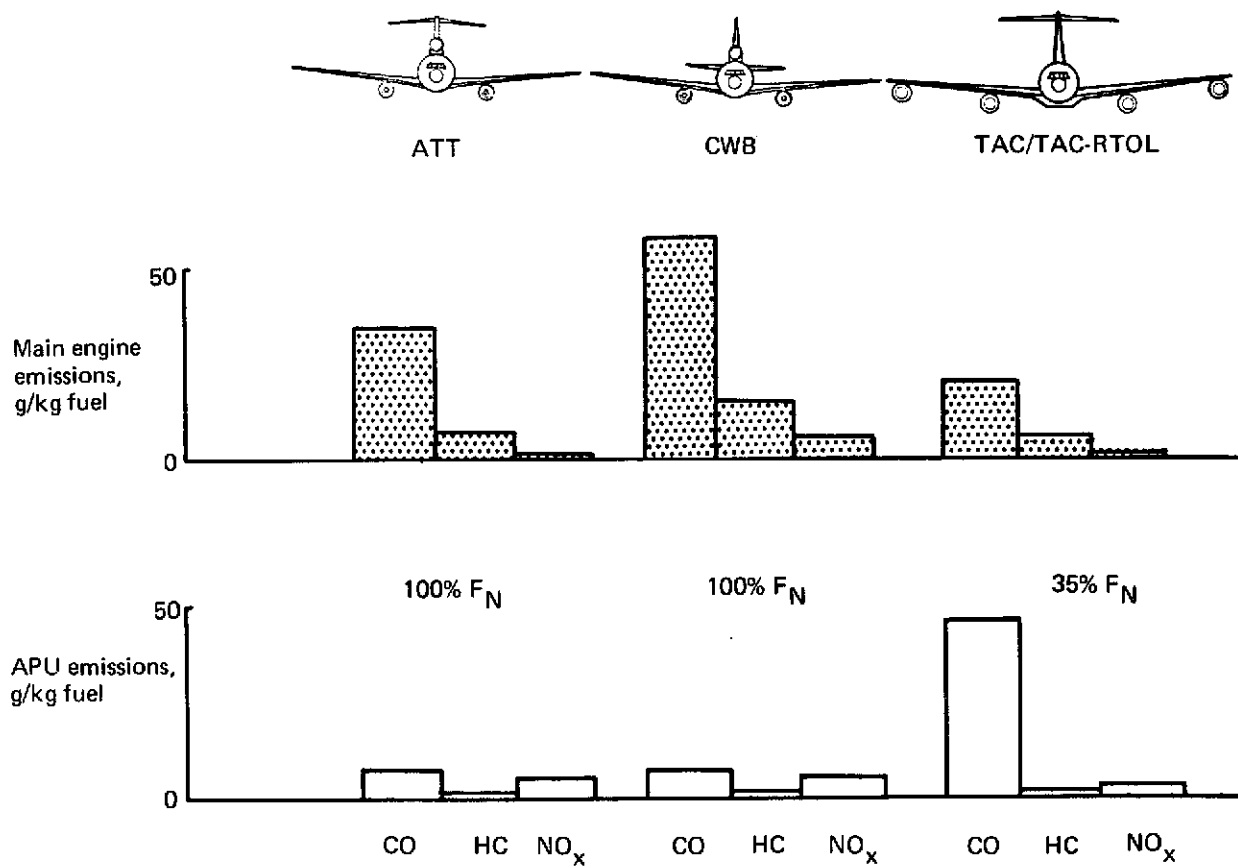


FIGURE 26.—COMPARISON OF EMISSION LEVELS FOR MAIN AND AUXILIARY POWERPLANTS

configurations by extrapolation of available test and research data. The prediction is based on correlation of empirical noise data supplemented by theoretical analysis, laboratory test and current aircraft and engine programs.

Engine source noise calculations were made separately for the turbomachinery and jet-noise components. Engine jet noise for both the primary and secondary streams is computed on the basis of relative velocity corrected for flow density and exit area. Separately, fan noise is computed based on number of parameters including fan-tip speed corrected for fan-pressure ratio, rotor/stator spacing, number of blades, fan diameter, and others. A composite spectrum (dB versus frequency) is then predicted for jet, fan, and inlet noise. Attenuation increments are then predicted based on defined levels of acoustic treatment. The attenuation is primarily dependent upon the number of rings or fan-duct splitters, the lengths and separation distances between the acoustic surfaces and upon technology level.

The attenuated fan spectrum is then combined with the jet noise at each frequency from which perceived noise level (PNL) is calculated. For a given airplane altitude and speed, PNL is used to calculate EPNL. Noise characteristics for an installed engine are then produced such as shown in figure 27. This figure illustrates the thrust and altitude relationship for engine noise for takeoff and approach conditions for both the CWB airplane engine and the advanced technology aircraft which all utilize the ATSA engine. The data presented in the figure is for a nominal engine size of 173 000N (40 000 lb) sea level static thrust. This engine noise data is scaled in the airplane performance computer program so that noise levels are presented for the sized airplane thrust requirement.

One change to the noise prediction methods has been made since the ATT study. This concerns the subject of airframe or non-propulsive noise which has recently been recognized as a potential noise floor particularly during approach operation. For the purposes of this program, although prediction and understanding of airframe noise is only now being developed, estimates have been made based on Contractor correlation of flight-test data supported by a theoretical analysis base. This correlation is sensitive to such operational parameters as airplane approach speed, gross weight, altitude, and overall parasite drag coefficient. Since these parameters potentially change between the four airplanes studied, some data are presented in later sections which will provide an estimate of the impact of airframe noise. Airframe and engine noise when combined are added on a time-history basis, assuming the airplane noise peaks at 60 degrees off the nose of the airplane. No airframe noise estimates were attempted for some of the steep descent drag devices which were added to the TAC airplane. A better understanding of airframe noise is needed in order to assess the nonpropulsive noise and to combine it accurately with the engine noise to obtain airplane flyover noise levels.

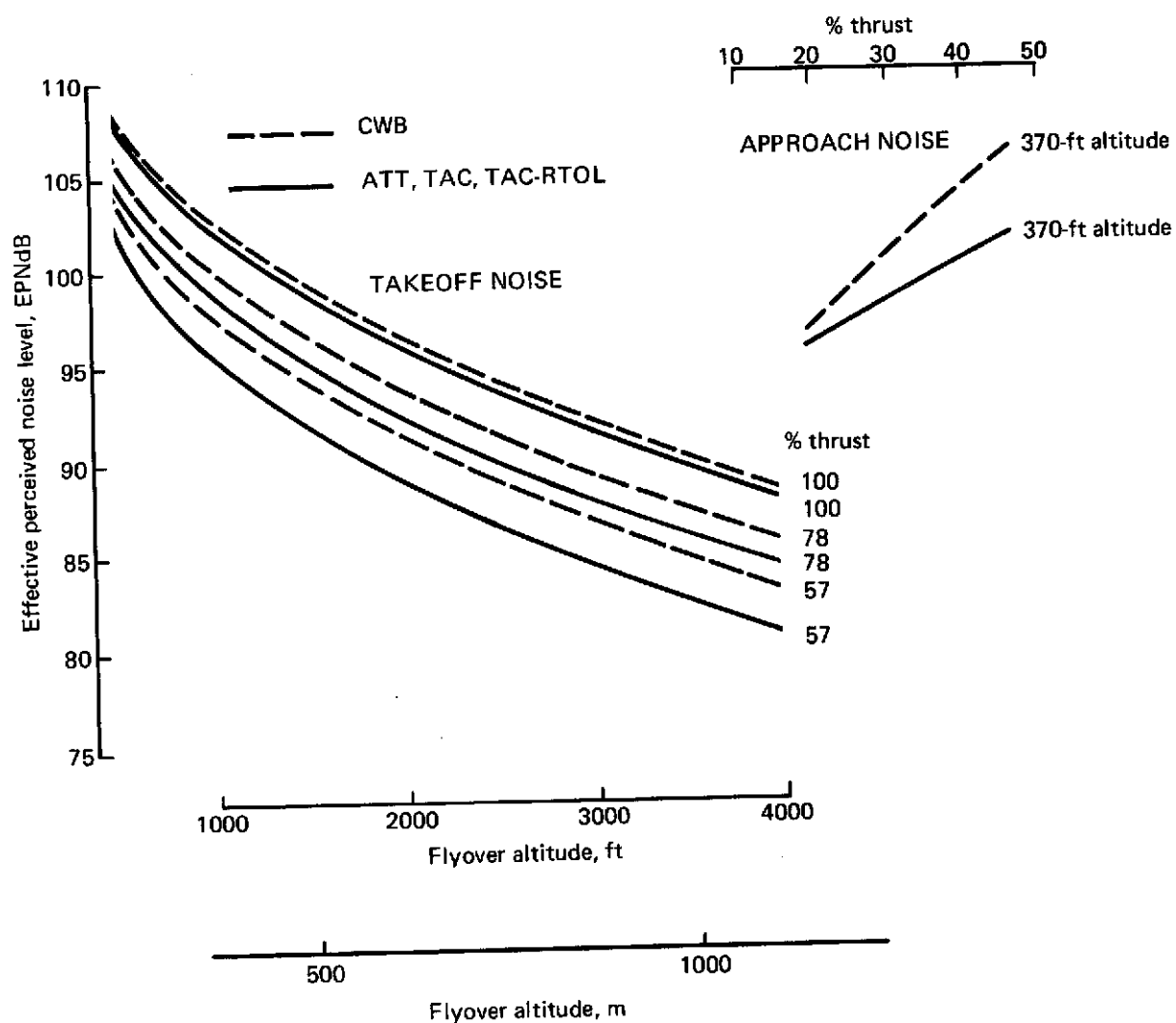


FIGURE 27.—COMPARISON OF AIRCRAFT ENGINE NOISE CHARACTERISTICS
(REFERENCE THRUST SIZE)

6.2.5 Flight Controls Technology

The flight controls data developed for the current study relied extensively on the stability and control analyses associated with the previous advanced technology program. The majority of the ATT analysis was directed toward developing a 0.98 cruise Mach number configuration. Both three engines on the aft body and four engines on the wing configurations were investigated in detail. Subsequently, a brief study investigated the economic technical impact of reduced cruise speeds down to Mach 0.95 and Mach 0.90. The Mach 0.9 configuration of that study (two wing-mounted and one aft-body-mounted engine installation) was selected as the baseline TAC study airplane. On initiation of the current contract a more detailed analysis on the original Mach 0.9 airplane resulted in some updating of the empennage sizing. Data for the four engines on the wing configuration selected for the TAC airplane were based upon similar four-engine Mach-0.98 configuration data also developed under the previous ATT contract. The three-engine current widebody technology (CWB) airplane was developed utilizing Boeing estimates based on DC-10/L-1011/747 technology levels.

All the advanced technology airplane horizontal tail sizes were selected to satisfy high-speed cruise trim cg considerations with the aft cg limit not constrained by static stability considerations but set by the critical most forward maneuver point encountered within the V/M flight envelope. Acceptable flying qualities would be provided by a full-time longitudinal stability augmentation system (SAS). When possible, a minimum horizontal tail size was chosen that satisfied both the high-speed stability and low-speed landing approach control requirements while providing the necessary cg loading range and performance required aft cg location. A comparison of the tail sizing of the TAC airplanes is presented in figure 28. This figure illustrates the selection of the minimum size and corresponding cg-limit boundaries for the four study airplanes. Relative to the CWB airplane aft cg limit, the ATT airplane shows a further aft cg stability limit which is a result of its relaxed inherent stability design criteria assuming a full-time SAS. Some of this aft cg limit is lost in going to the TAC airplanes as a result of increased cruise aeroelastic losses associated with the high-aspect ratio 9.0 wing. The relaxed CWB airplane forward cg limit established for landing trim and control considerations is a result of an assumed simpler flap system with inherently less nose-down pitching moment. Since the loading range is of the same order of magnitude for all four airplanes, the net result is a somewhat larger tail size for the TAC and TAC/RTOL airplanes than for either the ATT or CWB airplane.

All the vertical tails for the advanced technology airplane configurations were sized to provide adequate low-speed engine-out control capability during takeoff and landing. Full-time lateral-directional stability augmentation was assumed to provide satisfactory cruise stability characteristics. Figure 28b illustrates the relative vertical tail sizes required by the four study airplanes for engine-out control. The CWB airplane was configured with a low horizontal tail which allowed

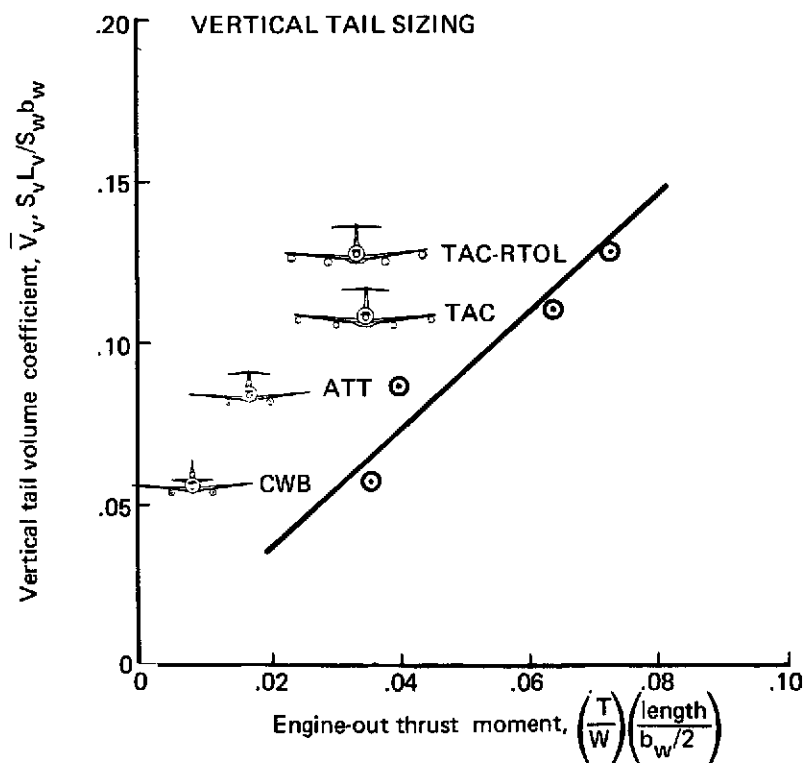
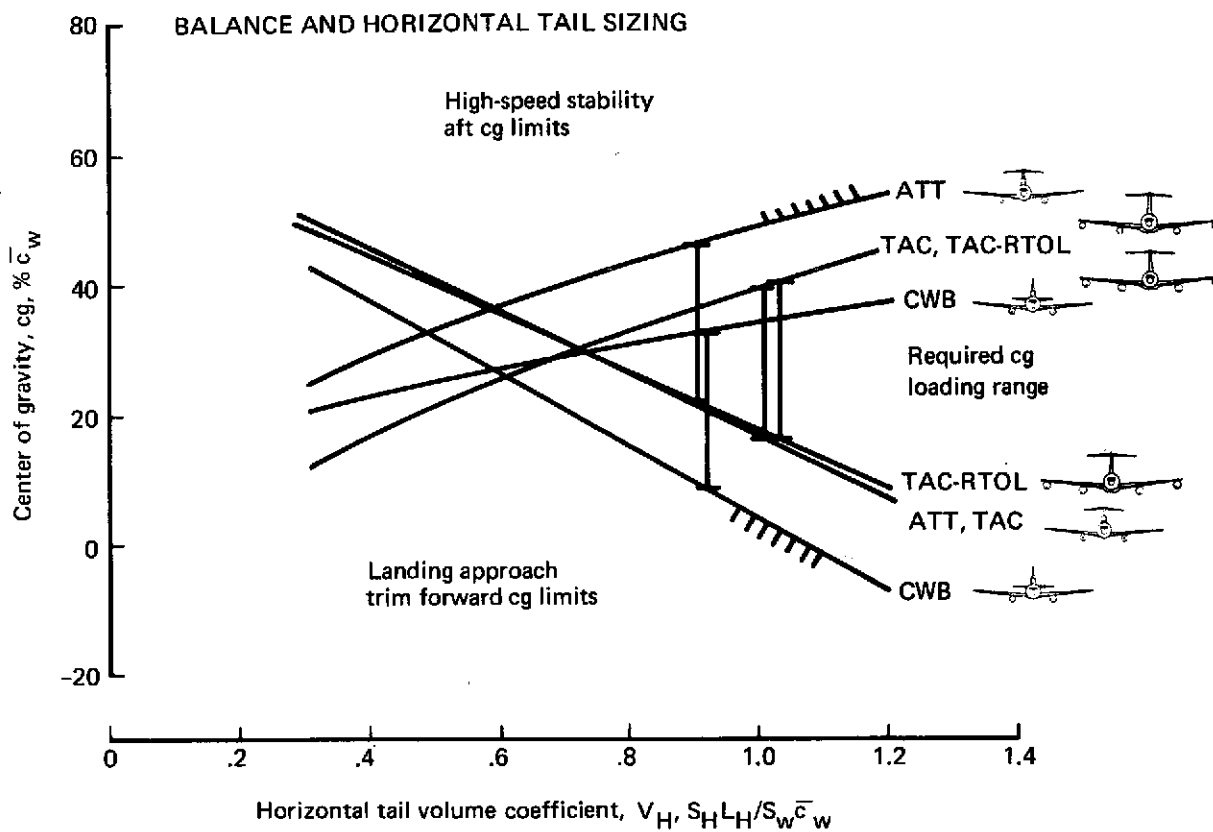


FIGURE 28.—COMPARISON OF EMPENNAGE SIZING—STUDY AIRPLANE

the use of a relative high-aspect ratio vertical tail planform. The more aerodynamically efficient CWB vertical-tail planform and large rudder span resulted in a relatively smaller vertical tail size required as shown in figure 28b. The ATT design was configured with a T-tail and S-duct center engine arrangement which limited the rudder span and available control power necessitating a larger vertical tail size as compared to the CWB configuration. Both the ATT and CWB configurations have comparable wing spanwise engine locations. The increased vertical-tail sizes for the TAC airplanes reflect the slower landing approach speed and further outboard engine location on a higher aspect ratio wing. The larger thrust size of the TAC-RTOL design accounts for an even further increase in tail size.




6.2.6 Systems Technology

6.2.6.1 Avionics Comparison

The main features of the avionics systems are shown in table 7. The baseline, TAC, and RTOL±Airplanes are essentially the same, with greater emphasis on integration of the descent, landing, and runway exit phase in the TAC and RTOL airplanes reflected through higher levels of system automation and improved displays. Major changes from current widebody airplanes to advanced airplanes include:

- a) More use of digital technology
- b) Flexibility enabling compatibility with changing ATC environment
- c) More accurate, automatic navigation/guidance
- d) Lower visibility landing
- e) Use of automatic equipment to augment the natural stability of the airframe, for greater freedom of balance conditions.
- f) More extensive monitoring of subsystems, for operational status and maintenance needs.
- g) Greater use of programmable CRT display systems.
- h) Grouping of elements by criticality, to achieve maximum, cost-effective redundancy requirements at minimal cost.

TABLE 7.— AVIONICS COMPARISON

Item	 CWB	 ATT	 TAC & TAC-RTOL
Capability			
External interface	Third generation ATC	Fourth generation ATC	Fourth generation ATC
Guidance	2D autonav	4D autonav	4D autonav integrated landing/ ground guidance
Low visibility landing	Category IIIa	Category IIIb landing monitor	Category IIIb landing monitor
SAS	Yaw damping and turn coordination dual	Relaxed inherent stability quadruple	Relaxed inherent stability quadruple
System monitoring	Distributed	Integrated automatic	Integrated automatic
Design philosophy			
Computation and data transfer	Analog and digital	Digital	Digital
Displays	Electromechanical	Electromechanical and CRT	Electromechanical and CRT
Physical division	By system and function	By criticality and function	By criticality and function
Reversion modes	As required	As required	As required

6.2.6.2 Mechanical Systems

The system areas affected appreciably by the terminal compatible features are the braking system, the landing gear, and the secondary power system.

Braking System—The brakes themselves, on all four airplanes, are similar to current steel brakes, but are somewhat larger on the TAC and RTOL airplanes, to accommodate the higher percentage of the airplane's kinetic energy that is dissipated in the brakes during a quick, high-deceleration stop.

The brake control systems of all four airplanes have conventional anti-skid capability. The flight control systems of the TAC and RTOL airplanes are also capable of scheduling the brake application to provide the desired total deceleration profile, including initial application (coordinated with spoiler deployment) as quickly as feasible after touchdown, a constant slope increase of acceleration, a constant acceleration phase, and finally a constant slope decrease of acceleration as the desired turnoff speed is approached.

Landing Gear.—The wheel design of the TAC and RTOL airplanes as shown in figure 29, is appreciably different than on current airplanes and the ATT airplane. The low-aspect ratio tire

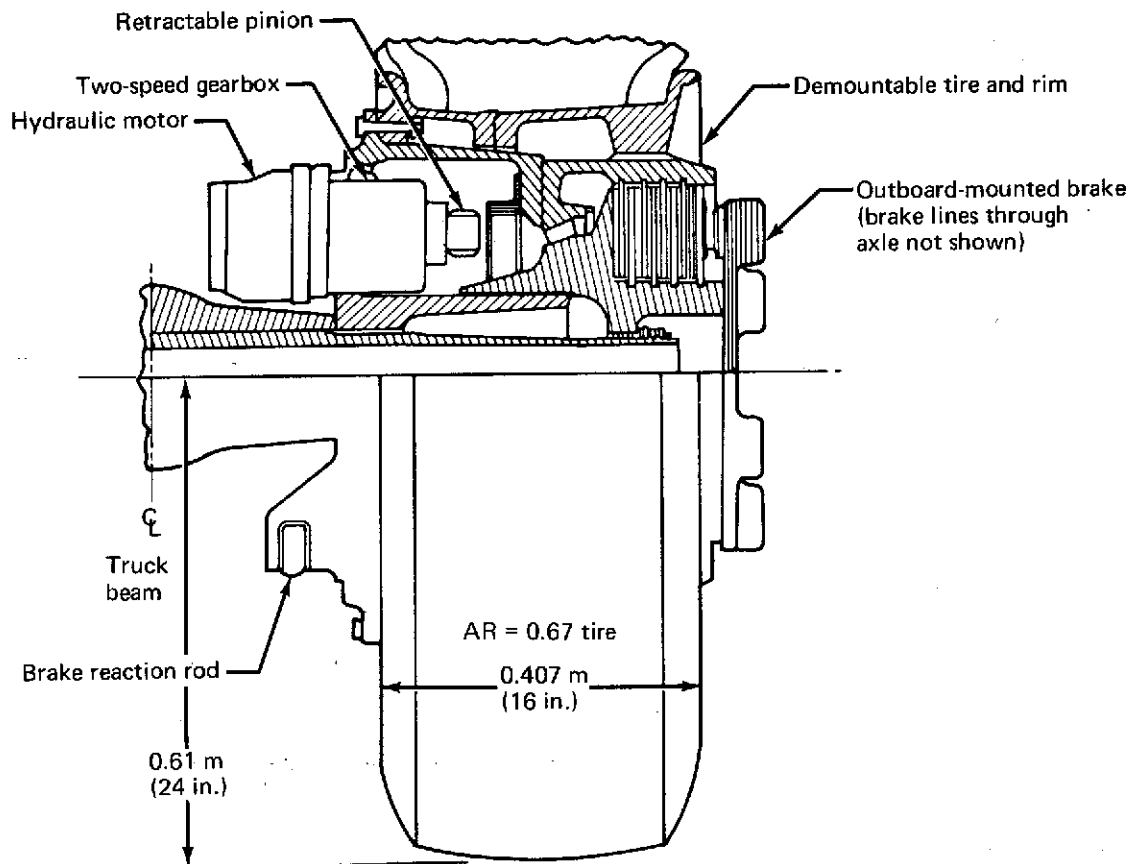


FIGURE 29.—WHEEL DESIGN WITH DRIVE MECHANISM

is used to allow more room inside the wheel for the taxi wheel-drive mechanism, the larger brakes, and portions of the anti-skid and automatic braking control system. The wheel-drive mechanism includes a hydraulic motor, mechanical gear changing and engagement mechanism, and the hydraulic supply lines. The placement of the components and the wheel attachment points are arranged for ease of maintenance, especially for the brakes. Detailed mechanical design of the landing gear has not been defined, but for each airplane is matched to the braking and ground-steering system dynamics for smooth, oscillation-free operation during all ground maneuvers.

The nose-wheel steering systems of the CWB and ATT airplanes are simple manual systems as used in present airplanes. In the TAC and RTOL airplanes, the nose-wheel steering system has automatic augmentation to give the commanded turning forces with dynamic and steady-state variations in nose-gear loading and runway friction characteristics.

Secondary Power System.—The secondary power systems are shown in figure 30. The basic constraints affecting the designs are: (1) electrical and hydraulic redundancy for fail operative SAS in all airplanes, (2) all anti-icing power supplied by APU in TAC and RTOL airplanes,

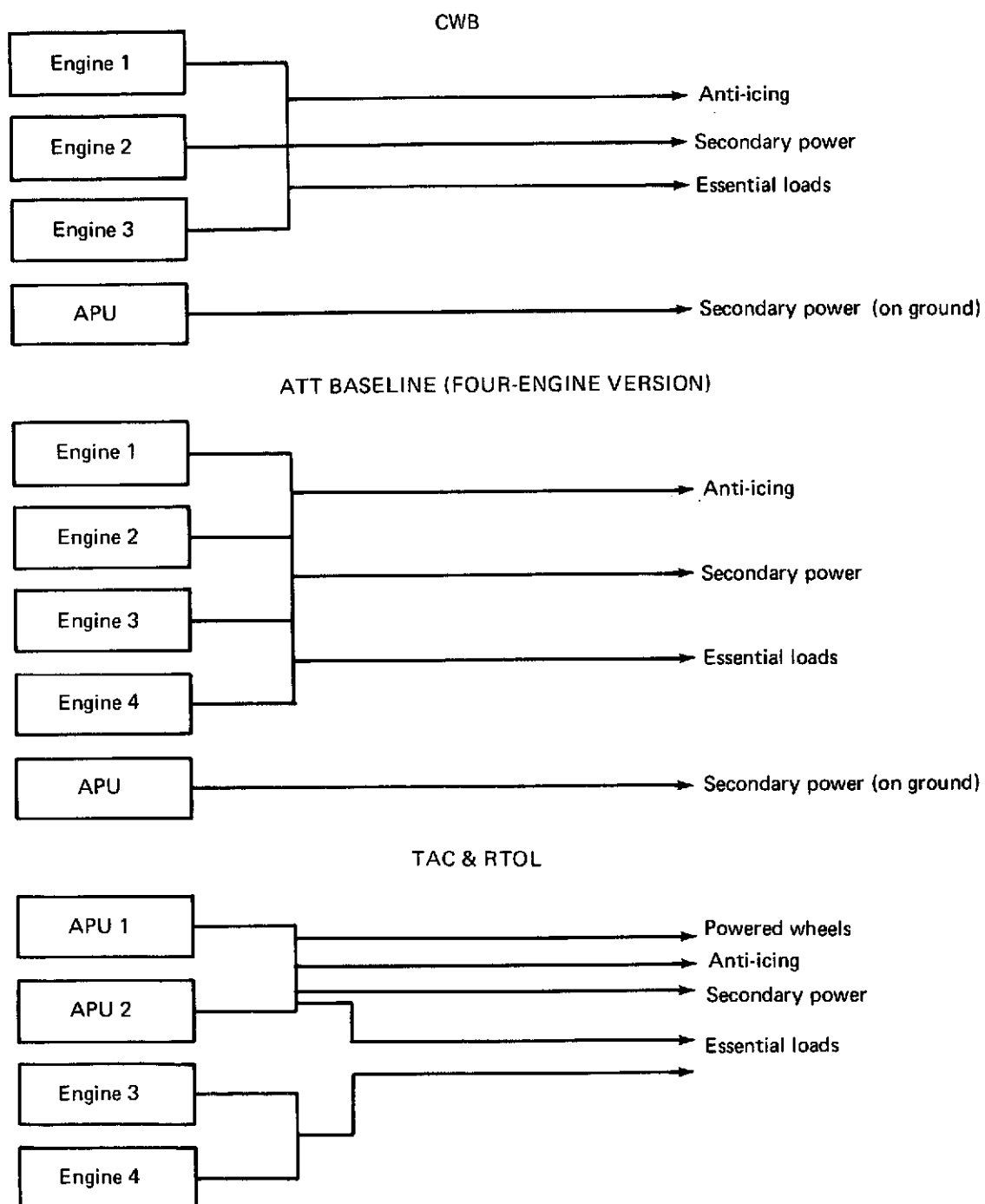


FIGURE 30.—AIRCRAFT SECONDARY POWER SYSTEMS COMPARISON

(3) APU not needed in flight in CWB and ATT airplanes, and (4) APU power for ground system and taxi power in TAC and RTOL airplanes.

The APU in the CWB and ATT airplane is a 445-kw (600-hp) conventional unit. For the TAC and RTOL airplane, two 1335-kw (1800-hp) advanced technology (lighter, more reliable) units are assumed.

The hydraulic systems for all airplanes are similar 3000-psi systems powered by four 75-gpm pumps. In the CWB and ATT baseline systems, all pumps are driven by main engines in flight, with power supplied by the APU on the ground. In the TAC and RTOL airplane, two pumps are operated by APUs and two by the inboard engines in all phases of operation. The TAC and RTOL hydraulic distribution lines are sized to supply power to the powered wheels as well as other loads, with valves to prevent powered wheel failures from affecting other systems.

Similarly, the CWB and ATT electrical systems are powered by 60/75-kVA generators on all engines during flight and by one such unit on the APU on the ground, while the TAC and RTOL airplanes have two generators on the inboard engines and one on each APU for all phases.

The pneumatic systems are similar on all the airplanes, except that on the TAC and RTOL all pneumatic power comes from the APUs rather than from the main engines. This eliminates the need for precoolers on the compressed air supplies, and requires minor changes in duct configuration and sizes.

In each airplane, there are various crossfeeds of power within and between pneumatic, electrical, and hydraulic systems for maximum effective redundancy appropriate to that airplane.

6.2.7 Weight Technology

Weight and balance analyses were performed for the CWB, ATT, TAC, and TAC-RTOL airplanes. Scaling rules were developed to assist in performance sizing the aircraft for comparable payload-range performance characteristics.

Weights for the ATT baseline airplane were developed from the weights as reported in reference 1 and from back-up documentation for that contract.

The weights for the CWB airplane were developed from previous studies of present-day widebodied airplanes.

The weights for the terminal compatible TAC airplane were estimated using statistical parametric weight prediction methods, because the change to a "four-engine-on-the-wing" installation resulted

in major configuration differences from the baseline trijet. The primary configuration effects considered were:

- a) Engine-out condition affecting vertical tail size
- b) Engine ground clearance affecting landing gear length
- c) Engine position on wing affecting wing strength and flutter material requirements.

The basic airplane weight was estimated by first applying the parametric-statistical weight estimation methods to a conventional technology, four-engined configuration without terminal compatible features. The advanced technology structural effects were then applied with weight benefits consistent with those reported for the ATT airplane. The total structural weight benefit was distributed as follows:

Wing	11.6%
Body	9.1%
Empennage	6.5%
Landing gear	8.4%

Weight penalties for each of the terminal compatible features were then applied. These increments are given in section 6.3.

An overall comparative weights breakdown of the four airplanes of interest is presented in section 7.0. Wing weight differences of interest because of the change in aspect ratio and area are shown in figure 31. The difference between the ATT and CWB is mainly due to advanced technology structure, wing area, and wing loading, although these wings also differ slightly in aspect ratio, thickness distribution, sweep angle, and taper ratio. Wing weight difference between the ATT and the TAC airplanes is primarily due to aspect ratio increase and area increase with smaller weight increments due to outboard engine location and dihedral angle discontinuity (gulling). The TAC-RTOL wing differs from the TAC wing primarily due to increased wing area with wing loading held essentially constant.

Fixed equipment weights for the airplanes of this study are essentially the same, except for the dedicated APU and secondary power systems for the TAC and TAC-RTOL. The new, large APUs used in these airplanes are advanced technology turbines with approximately 40% improvement in power/weight ratio compared to currently employed APU turbines.

Standard and operational items weights were based on rules consistent with those used for the ATT studies.

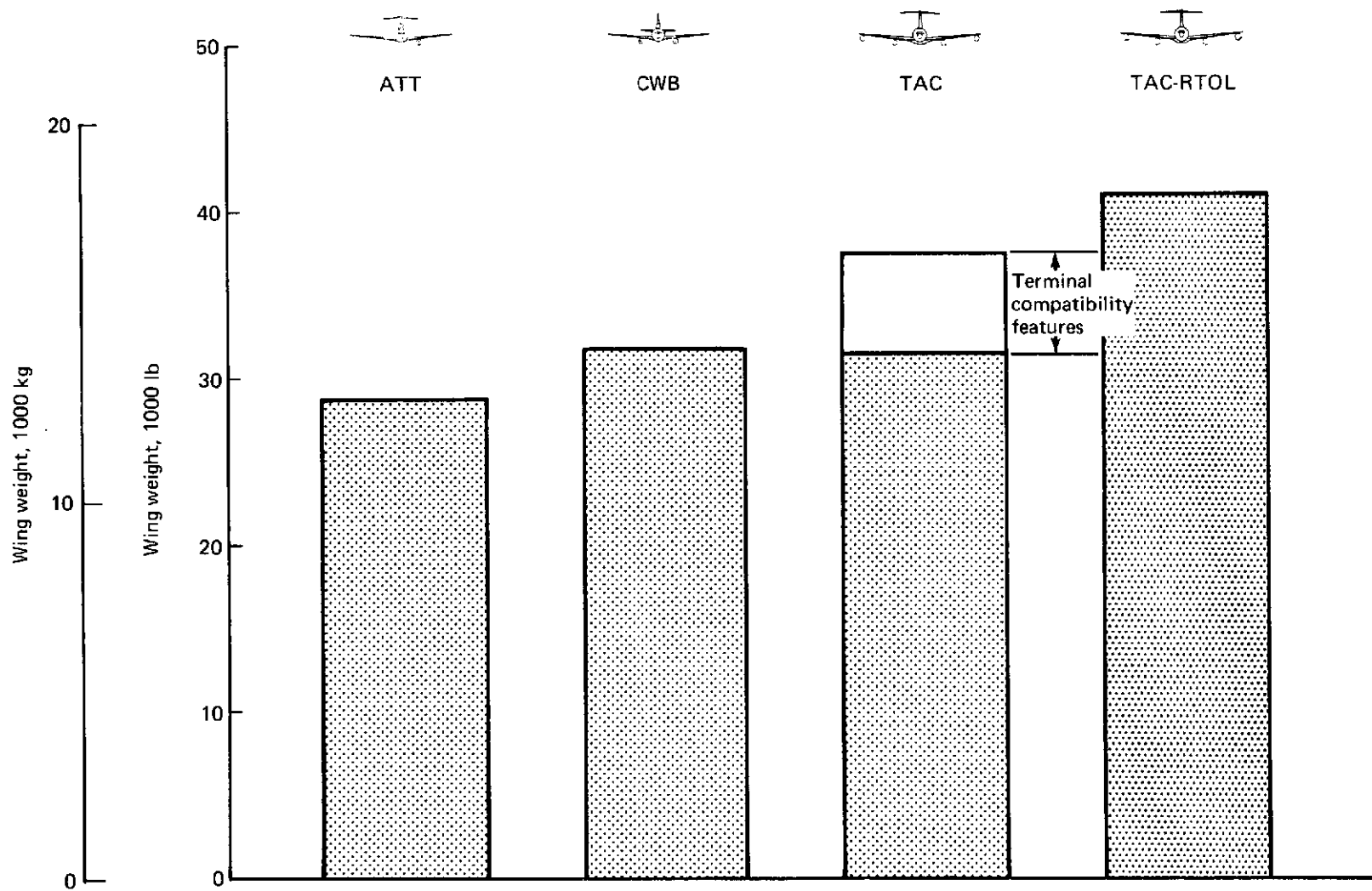


FIGURE 31.—WING WEIGHT COMPARISON

6.3 DETAILED TERMINAL COMPATIBILITY FEATURES

In this section the major design changes made to the ATT airplane to incorporate terminal-compatibility characteristics are described. Figure 32 gives an overview of the major design changes which are then described individually in some detail beginning in section 6.3.1. The major change was from a three-engine to a four-engine airplane. This was done to provide flexibility for positioning the outboard engines near the wing tip as a method of tip vortex control. Tip vortex control was also the motivation for the mechanical device shown at the trailing edge of the outboard wing position.

The reasons for these two design changes will be discussed in more detail in section 6.3.1. The second design change concerns an increased by some 27.8 m^2 (300 sq ft). The motivation here was improved, low-speed aerodynamics which was used to reduce the airplane noise impact on the community. A third design change which the reader will note in the aft end of the TAC airplane fuselage was the incorporation of large drag brakes which deploy from the fuselage. This design change was motivated by the requirement for achieving steep descents for the purpose of noise abatement on approach.

Some changes have been made to the engines primarily by assuming the incorporation of an advanced combustor to improve engine emissions. A smaller change involved a slight modification of the engine cycle toward reduced overall pressure ratio, again for the purpose of emission reduction.

An additional modification included incorporation of a powered-wheel device for providing low-speed taxi without the use of the main propulsion engines. Incorporation of the powered wheel required increasing the size (relative to the ATT airplane) of the auxiliary power unit to drive the wheel. At the same time the APU was oversized again in order to provide an in-flight APU capability for driving all the auxiliary power systems of the TAC airplane. For reasons which will be discussed in more detail in section 6.3.4, this design modification was made in order to effect additional noise reduction through the ability to realize lower throttle settings for the airplane on approach.

Further design changes made to the airplane included increasing the braking material in each of the landing gear wheels in order to provide the capability for high-speed deceleration without compromising brake life. The landing gear, including both the main gear and the nose gear, were reviewed for structural soundness to accomplish the high-speed turnoffs which were deemed desirable for improved congestion reasons. The results of this review will be discussed later.

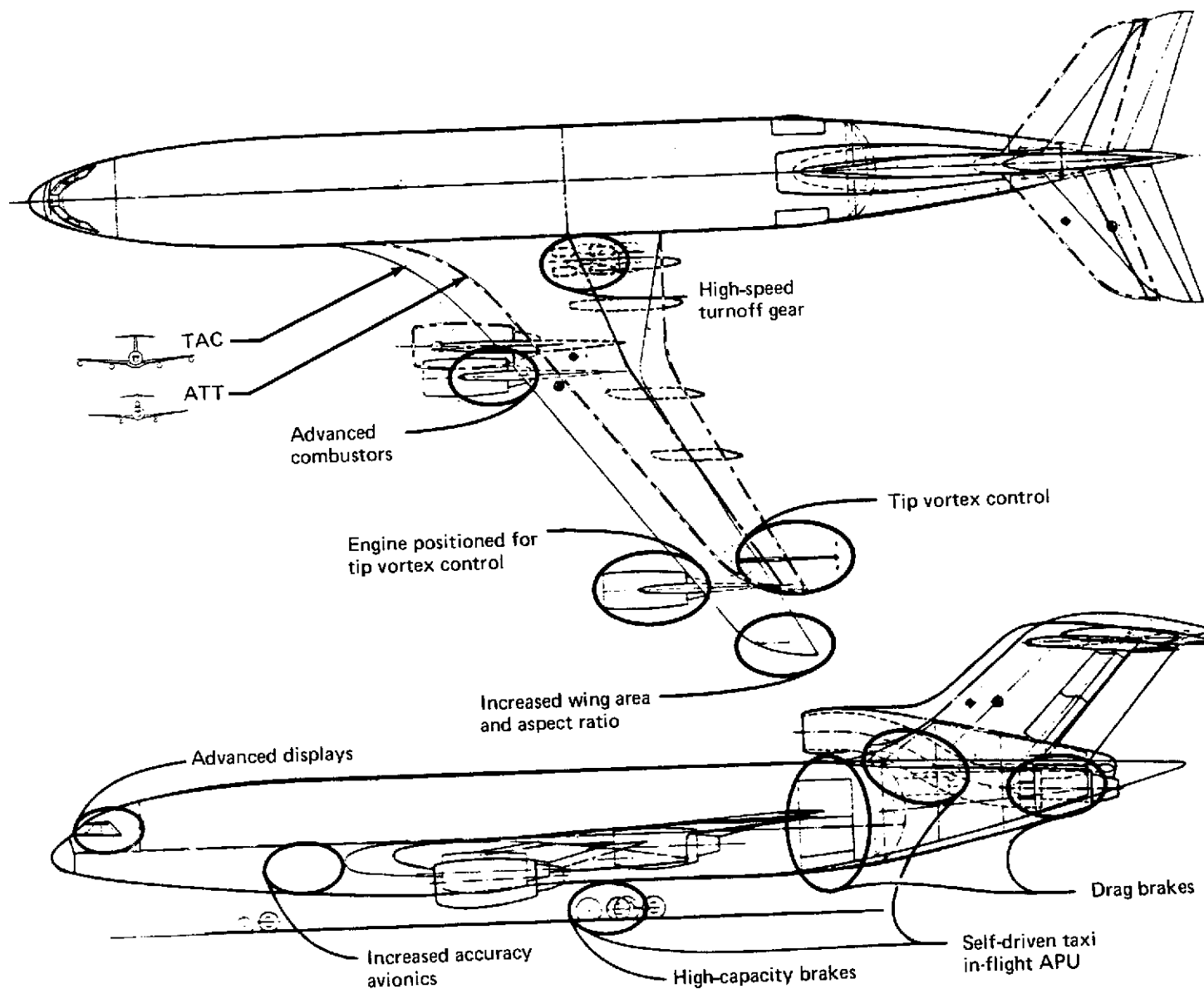


FIGURE 32.—PRINCIPAL DESIGN IMPACT OF TERMINAL COMPATIBILITY

A number of modifications were made to the airplane avionic system in several areas as shown in figure 32. Improved displays were incorporated in order to enable the pilot to perform some of the desirable operational procedures such as steep descents, passenger-tolerated high deceleration rates, and high-speed turnoffs. These advanced displays were deemed necessary in order that pilot workload be kept to levels consistent with current airplane operations. Beyond that, the navigation and guidance system of the airplane was also upgraded in order to provide (in conjunction with ground-based ATC equipment) an increased accuracy in knowledge of where the airplane is in time at a given point in space.

The remaining sections in this chapter discuss in some detail each of the above changes, why they were made, what design criteria were established to guide the change, what design approaches appeared as options, which approach was selected and why, and finally, some of the unknown design risk areas associated with the selected design approach.

6.3.1 Wing Trailing Vortex (Wake Turbulence) Modifications

The basic motivation to establish a design change to control aircraft wake turbulence is shown in figure 33. This figure shows runway acceptance rate plotted against aircraft in-air separation distances while parametrically varying outer market delivery accuracy. The in-air separation distance is the required spacing, for safety purposes, between two successive aircraft on an approach glideslope. The outer market delivery accuracy is an indication of the state of knowledge of where the aircraft will be in time at a given point in space. Typically, in today's operations this knowledge is established to an accuracy of within 18 seconds. In-air separation rules require between 5.56 and 9.26-km (3- and 5-mile) distances depending upon airplane size. The curve illustrates the potential doubling of runway operations if in-air separation levels can be reduced and simultaneously the time-wise knowledge of where the airplane is can be increased.

It is important to note that the technology for evaluating and controlling wake turbulence is still in its infancy. Thus, a great deal of knowledge is still lacking in terms of defining specific design approaches. However, as the figure shows, a number of approaches have been proposed by various investigators. These span a range of solutions including changes which can be made to the airplane and approaches which leave the airplane intact but require changes to ground facilities. Within the scope of the current study *with its emphasis on modifications to the airplane* a design approach was selected from those candidates which apply to airplane changes.

In arriving at the selected approach discussions were held with representatives of the NASA to establish recommended directions based on some of the technical work which has been recently initiated in various branches of that agency. Again, emphasizing the early stage of the investigations, NASA analysis and testing had encompassed a number of design approaches to the airplane for

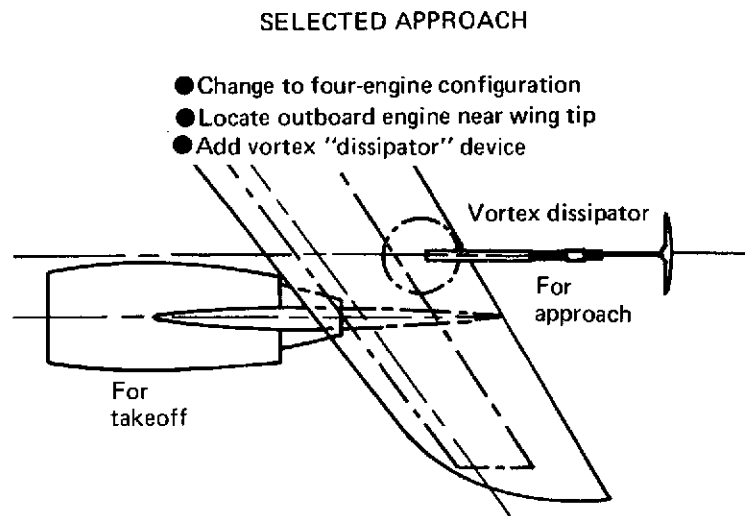
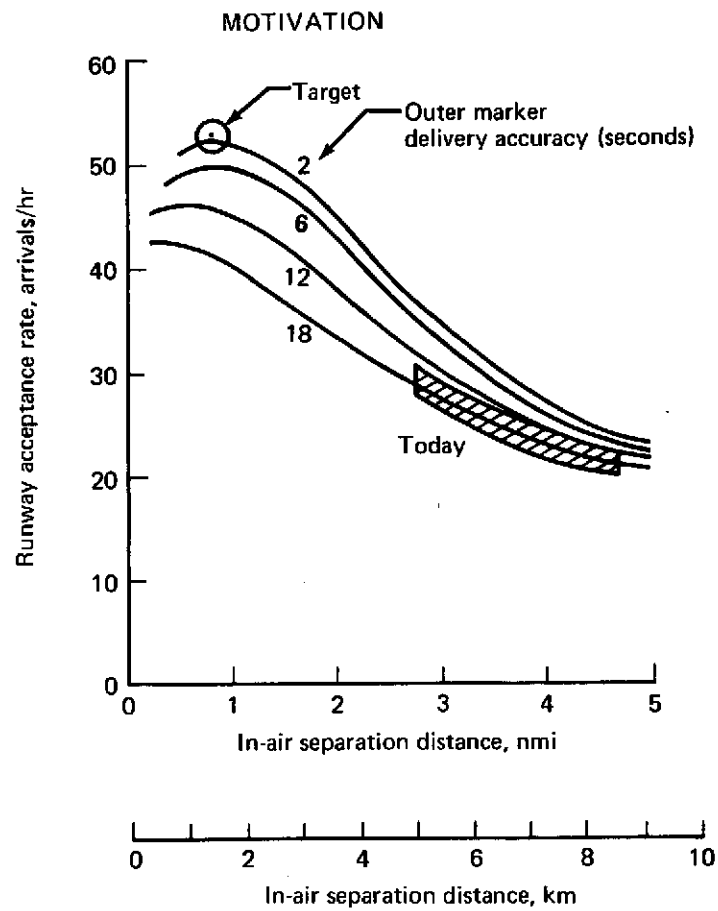


FIGURE 33.—TERMINAL-COMPATIBLE FEATURES—WING-TIP VORTEX (WAKE TURBULENCE)

the purpose of wake turbulence control. These included: injecting large masses of air directly into the wing vortex; utilizing some kind of blockage device trailed behind the wing which would protrude directly into the tip vortex; redesigning the lift distribution on the wing in a spanwise direction to make an effort towards a distributed rather than a concentrated tip vortex; and other approaches such as various end plates, vortex generators, or other devices installed directly in the wing tip area in the hope of modifying and breaking up the tip vortex.

As a result of the discussions with the NASA investigators and also on the basis of the earlier task II studies, a number of design criteria were established. These criteria recognized the need for tip vortex control for both takeoff and approach operations. They required that improvements to congestion would try to avoid adverse impact to the noise and emissions problem (the other elements of terminal-area compatibility). More specific criteria were established in some cases as a result of the NASA studies where, for example, it was shown that the approach utilizing mass injection required relatively large rates of air. Also, relating to the various proposed drag devices, operational requirements imposed the constraint that if such devices are deployed during approach they must be capable of rapid retraction in the event of an airplane go-around.

Of the various design approaches studied by the NASA, several were rejected for the purpose of this study on the basis of the limited data available. These included many of the proposed wing-tip modifications. Based on the early data, these proved to modify the tip vortex in the near-field region of the wing trailing edge, but this effect was generally shown to be local in nature and in fact, the tip vortex often reformed shortly thereafter downstream. The idea of aerodynamically designing the wing to provide more optimally distributed spanwise loading is an attractive one, however, no data were yet available to provide an indication of the effectiveness of such an approach or the possible penalties. Similar comments hold for proposals to introduce variations in flap and aileron deployment in the hope of promoting tip-vortex instability.

Of the various NASA studies, qualitative model data in the form of flow visualization studies indicated that massive amounts of air injected directly into the wing vortex did provide some measure of vortex control. Similarly, the flow visualization studies indicated promise for some kind of blockage device which would be deployed from the trailing edge of the wing and positioned in the path of the tip vortex. It was on the basis of these studies that the design approach utilized for the TAC airplane was selected.

In fact, in order to achieve a solution for both takeoff and approach, two vortex control methods were adopted. The reasoning was this. The requirements for massive amounts of air injection into the tip vortex could be accommodated by locating the primary propulsion engine out near the wing tip. This solution was satisfactory for takeoff where high levels of thrust are normally desirable and achieved anyway. However, high levels of thrust are not compatible with

the various approach requirements including noise levels. Similarly, the utilization of a blockage or drag device deployed from the trailing edge of the wing appeared suitable for approach operations and in fact for steep descents the airplane was in need of additional drag anyway. However, such a procedure would not be suitable for takeoff operations where additional drag would require oversizing of the engine and considerable penalties would be incurred.

Thus, the design approach adopted for this study was to select a four-engine on-the-wing arrangement and to reposition an outboard engine near the wing tip, although the specific location could not be evaluated because of lack of data. Operation at full throttle of this engine would be used to control tip vortices during takeoff. During approach with the engines throttled back and presumably ineffective to control the tip vortex, deployment of the mechanical vortex dissipator device would be used.

The design approach incurred several penalties which included weight increases associated with moving the outboard engine from a normal spanwise location of 70% span to a tip-vortex control location which was estimated to be on the order of 85% to 100% span. Additional penalties are incurred as a result of increases required for the vertical tail to control engine-out conditions. The mechanical dissipator device and its actuation and assembly also added weight. Some additional drag was charged to the installation including the drag associated with enlarged vertical tail and fairings for the vortex dissipator. Potential aerodynamic drag penalties associated with integrating the outboard nacelle with the high-aspect ratio wing also exist. These latter penalties, however, could not be assessed without wind-tunnel data and *were not incorporated into the analyses of the TAC airplane*. Some penalty is paid in terms of increased noise on a three-degree approach because of the increased engine throttle setting required to compensate for the vortex-dissipator drag when the device is deployed.

It is emphasized that because of the lack of detailed design data, there are a number of high-risk areas involved in the design approach adopted. These include the effectiveness of the vortex control measures chosen since the data base on which the selection was made was qualitative rather than quantitative. Moreover, the data did not enable rational selection of engine position, placement, or vortex dissipator position or sizing. Furthermore, it is not clear to what extent overall airplane lift and drag is affected by utilizing the engine or dissipator devices in the ways described. Questions exist concerning the potential flutter problems if the spanwise location of the outboard engine is required to exceed a certain distance. Results of a limited study conducted under the current contract indicated that large flutter penalties could be avoided provided the outboard engine was located inboard of a 90% spanwise location. For the TAC airplane, a 85% spanwise location was selected. It is not known, of course, whether this is consistent with the required vortex control. Several design layouts were made for various vortex dissipator concepts. However, detail designs were not attempted, and risk areas include mechanization and operational practicality.

6.3.2 Low-Speed Aerodynamic Improvements

Two separate reasons to modify the low-speed aerodynamics of the basic ATT airplane were identified and these are shown in figure 34. First, task II studies showed that runway acceptance rate can be improved by about 30% relative to today's condition provided approach speeds can be reduced from 69.5 m/s (135 kn) (baseline ATT approach speed) to approximately 61.8 m/s (120 kn). This enables reduced ground rollout times following touchdown and reduces runway occupancy time. The second reason for improving low-speed aerodynamics was takeoff noise. As shown in the figure, the baseline ATT airplane relative to 15 EPNdB below FAR Part 36 (contract goal) was fairly close in terms of sideline noise, several EPNdB above due to approach noise but on the order of six to eight EPNdB above the goal on takeoff noise. The figure also shows that in terms of NEF contours for the ATT airplane the total area was dominated by noise imposed by takeoff operations.

It was concluded that a reasonable approach to reduce takeoff noise is to provide the airplane with improved climbout gradients. This capability could then be used to provide either increased height above the community as a noise buffer or to reduce the thrust necessary to maintain the required climb gradient under thrust cutback operation. Several design options existed to achieve the objectives of reduced approach speed and the improved takeoff-climb gradients. These included: additional engine thrust, increased flap area, increased wing area or improved low-speed lift-to-drag (using either a high-aspect ratio wing or reduced wing sweep).

Several design criteria were established to guide the low-speed aerodynamic design changes. One ground rule was to retain Mach 0.9 cruise capability for the advanced technology airplane. In addition, based upon design studies conducted previously in task II effort, it was estimated that an increase in height of 91 to 152 m (300 to 500 ft) over the community at the noise takeoff measuring station would accomplish the required noise reduction. A 61-m/s (120-kn) approach speed was specified based upon runway rate considerations.

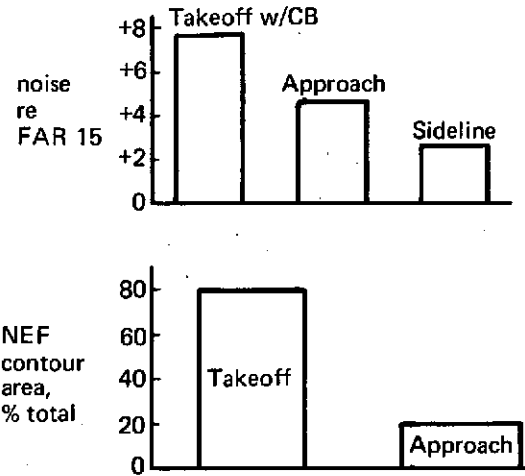
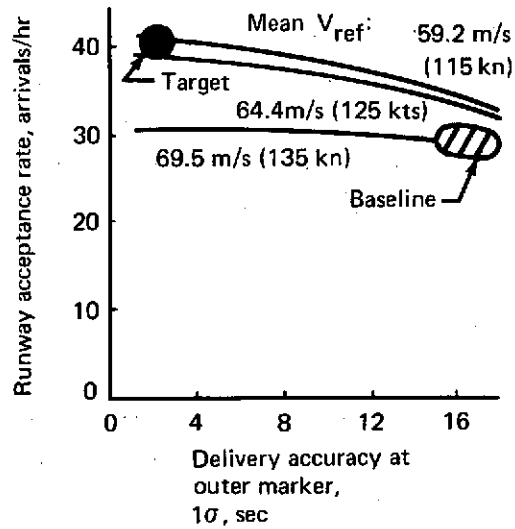
In reviewing various design options, increased engine thrust and increased flap capability were ruled out since neither were able to achieve both the approach speed and takeoff noise goal by themselves. Increased wing area had been studied previously during the ATT study and was shown to be uneconomical if utilized alone. Changes to wing sweep and thickness, although potentially useful, were not adopted in order that cruise Mach number would not be compromised.

Thus, the design approach selected for the TAC airplane was to employ a higher aspect ratio wing. As shown in figure 34, increased aspect ratio had the advantage not only of improving the climbout gradient, because of its improvement to low-speed aerodynamic performance, but also reduced approach speeds. The data shown, developed in a brief design study, indicated that an

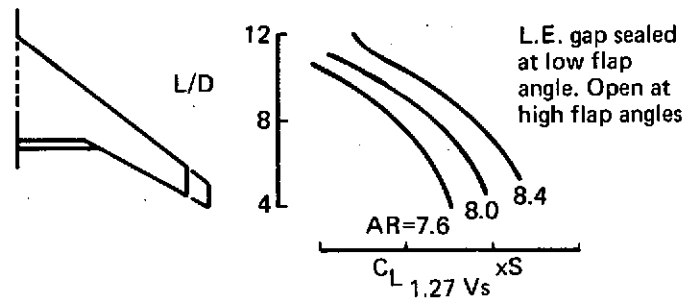
MOTIVATION

(a) Need to reduce approach speed

(b) Need to improve ATT takeoff noise



SELECTED APPROACH



DESIGN SIZING

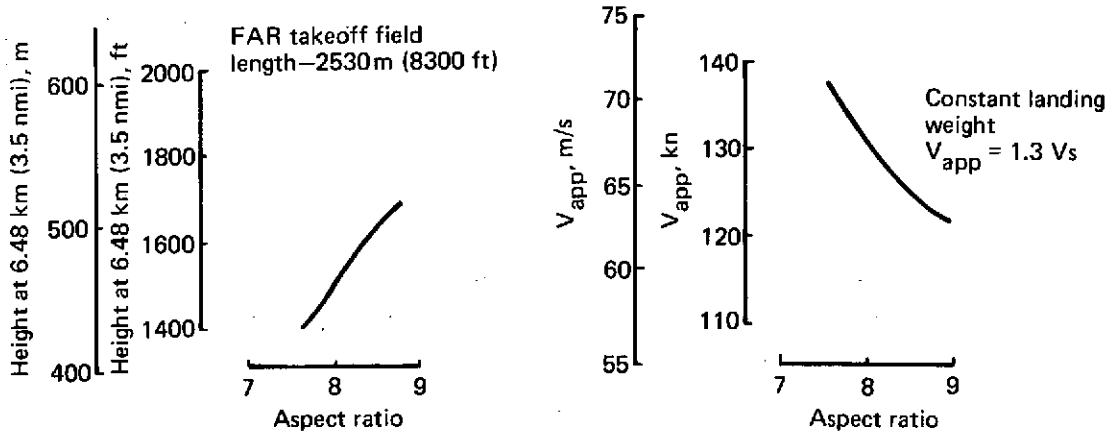


FIGURE 34.—TERMINAL-COMPATIBLE FEATURES—LOW-SPEED AERODYNAMIC IMPROVEMENTS

aspect ratio on the order of 9.0 would accomplish the design goals.

There are several design-risk areas associated with the modifications proposed for the TAC airplane. These include potential low-speed pitch-up tendencies due to the aspect ratio 9, 36.5-degree sweep wing. Some evidence exists that separation on the outboard portion of the wing may be difficult to control. Secondly, the question of successful aerodynamic integration of the high-bypass ratio engine at an outboard spanwise location on a high-aspect ratio (i.e., small chord) wing may be difficult to achieve without undue penalties. The aspect ratio 9.0 wing in combination with high-bypass ratio engines is not a configuration for which considerable previous design experience exists.

6.3.3 Steep Descent Capability

The basic motivation for providing the TAC airplane with steep descent capability can be seen from figure 35b. This plot shows the centerline noise level under the flight track of an airplane employing: (1) a straight three-degree glideslope, (2) a two-segment six-degree/three-degree glideslope, and (3) a two-segment nine-degree/three-degree glideslope. It can be seen that continual improvement is shown in reducing the 90 EPNdB approach noise contour centerline closure as the upper segment glideslope is increased to nine degrees.

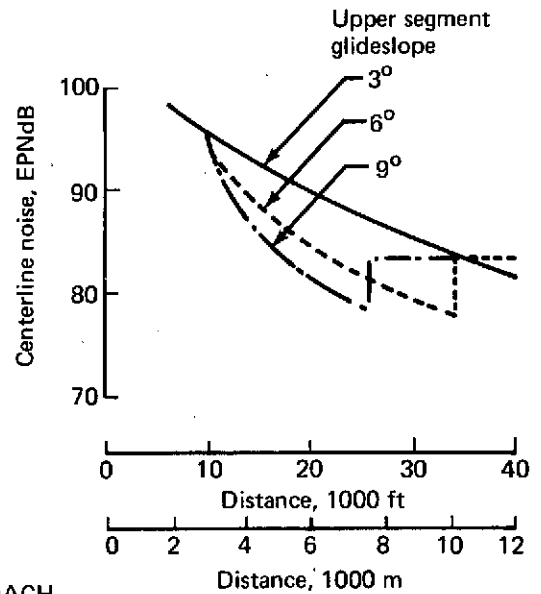
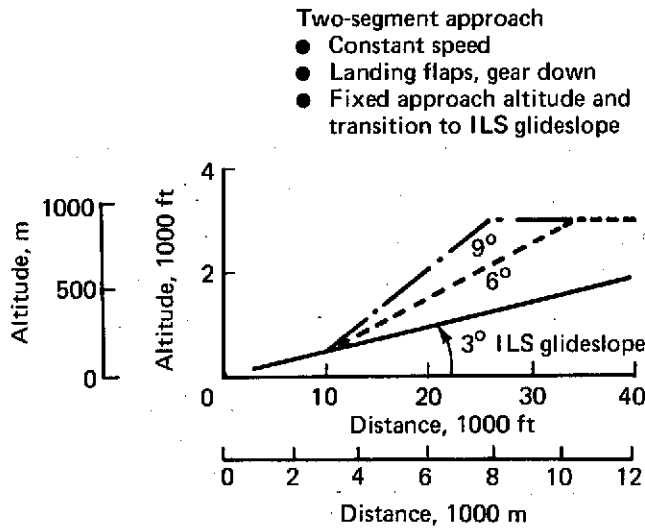
Calculations developed during task III showed that the ATT airplane would accelerate on a nine-degree approach path if additional drag is not available. Several design options are available to maintain a nonaccelerating approach which include increasing the drag-brake area available on the wing surface, utilizing in-flight thrust reversing, or finding other airplane areas from which drag surfaces might be deployed. In assessing the various options available, wing-speed brakes were ruled out because of their anticipated tendency to aggravate wing buffet. In-flight thrust reversers, although perhaps a promising approach, were not adopted because of the potential increase in noise which could not be assessed accurately. However, it was noted that at some airports already, the tendency exists towards reducing the use of thrust reversers even during ground roll because of the community noise impact.

The design criteria established to guide the steep descent airplane design modifications included the following. The design goal was to provide the airplane with the capability to handle a nine-degree/three-degree two-segment landing approach. A transition from the upper glideslope to a current three-degree glideslope was fixed at 152 m (500 ft) altitude consistent with pilot comments made during current flight tests of the existing aircraft during noise-abatement approaches. The use of a two-segment approach reduces the community area noise without fears of adversely affecting aircraft safety by increasing the descent rate close to the ground which

MOTIVATION

(a) Need to steepen approach profiles

(b) Need to reduce centerline approach noise



SELECTED APPROACH

- 9°/3° two-segment glideslope approach

DESIGN SIZING

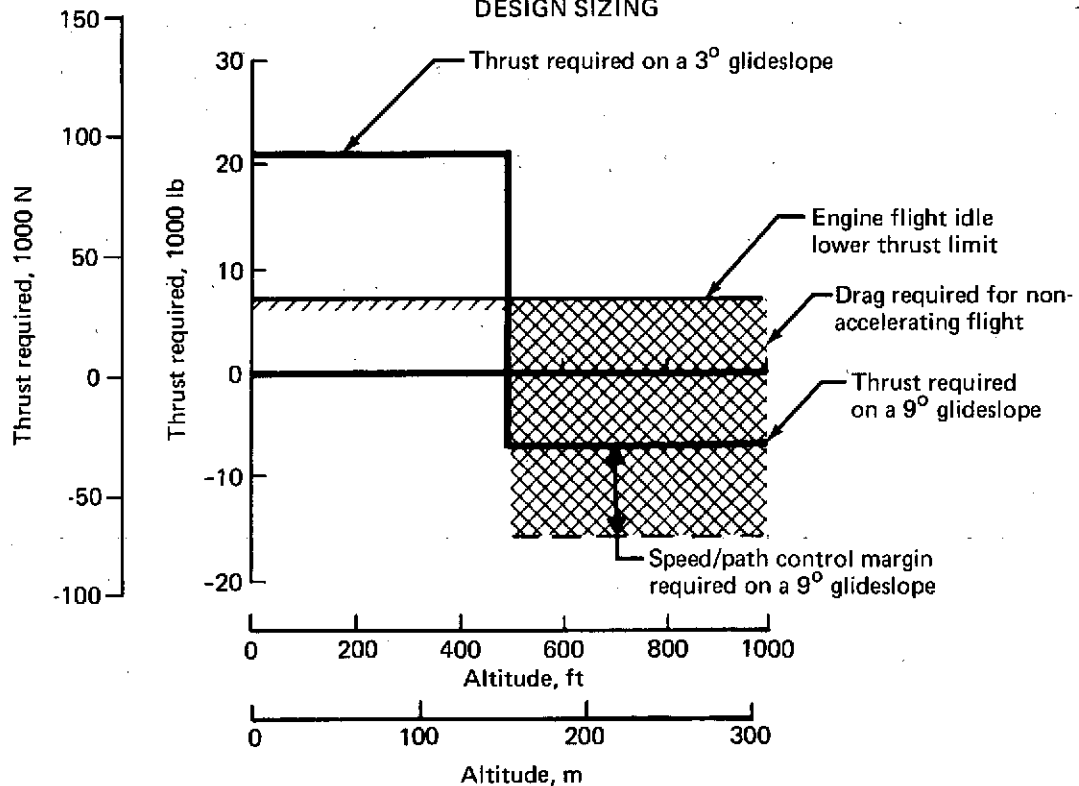


FIGURE 35.—TERMINAL COMPATIBLE FEATURES—STEEP DESCENT CAPABILITY

would be a consequence of a straight-in steep glideslope approach. For simplification, all calculations were made assuming a constant speed, fixed configuration (landing flaps, gear down). Additional design criteria were established which required sufficient speed and flightpath control capability to handle unanticipated glideslope errors and shearing tailwinds.

The design approach adopted to obtain the necessary drag consisted of utilizing deployable aerodynamic drag brakes configured at the aft end of the airplane fuselage. This approach is similar to a design feature of the existing Fokker F-28 airplane, although the TAC drag panels are considerably larger. The chart at the bottom of figure 35 gives an indication of the thrust required on a nine-degree/three-degree two-segment approach. Aerodynamic drag (shaded region) is required on the nine-degree upper glideslope to maintain nonaccelerating flight as the thrust required falls below the lower flight idle limit. Additional drag is required for speed and path control in order to land in a shearing tailwind. Making the assumption that the minimum flight idle thrust setting limits further thrust reduction, additional drag, approximately equal to the low-speed drag level of the airplane in level flight, must be added to the airplane to implement a nine-degree glideslope steep descent approach.

Again, considerable design risk and uncertainty exist with respect to the proposed airplane modifications. These include a lack of knowledge concerning aerodynamic flow interference of the deployed drag panels with respect to the empennage surfaces. Similarly, the fail-safe operation of such drag panels has not been considered but is, of course, an important consideration. Study is required to determine the complexity of integrating the drag device with the airplane flight control system to operate effectively. Although preliminary conceptual designs were established for the drag-device mechanization, questions exist concerning potential interference of this mechanization with the pressurized fuselage structure. Finally, concern exists over the impact on airplane airframe noise, i.e., nonpropulsive noise, which is expected to increase as a result of the deployed aerodynamic drag panels. Insufficient data exist to make an estimate of the potential airframe noise penalty which might be realized relative to the overall noise improvement achieved through the steep approach path.

6.3.4 Improved Pollution Technology

As discussed previously in section 5.0, the principal motivation of aircraft engine emission control is to establish pollutant tonnages to levels which are consistent with satisfactory ambient air quality. The various design options available include both changes to the airplane and changes to the engine itself:

- a) Reduced airplane ground operation
 - 1) Reduce delay

b) Reduced "low-power" engine operation

- 1) Powered wheel
- 2) Fewer engine taxi

c) Improved combustor design

d) Varied engine cycle

- 1) Lower OPR
- 2) Lower T_4
- 3) H_2O injection

As shown in task II, improvement to airplane ground congestion will by itself contribute significantly to reduction of carbon monoxide and hydrocarbons. Similarly, if aircraft operations are such that fewer engine operations are conducted on the ground at low-power settings, then improved carbon monoxide and hydrocarbon emissions also result. Finally, projections have been made of the potential direct reduction of engine emissions for hydrocarbons, carbon monoxide and oxides of nitrogen by various proposed combustor modifications.

The design criteria for the TAC airplane have been established by the NASA. As shown in figure 36, levels have been prescribed in terms of pounds of pollution per thousand pounds of fuel for the three pollutants of interest in the study. The figure also indicates, for comparison purposes, values for today's JT9D combustor technology and also equivalent levels determined relative to an EPA-developed emission parameter used by that agency to prescribe future aircraft standards. Finally, levels are shown for predicted pollution indices based on studies conducted by two aircraft engine manufacturers under the previous ATT contract.

The design approach selected for the current study is also indicated schematically in the figure. The approach has been that to control hydrocarbons and carbon monoxide the advanced combustor technology projections established by the engine manufacturers are used to the fullest extent. It can also be seen from the data presented that these projections did not provide sufficient pollution reduction to comply with the study goal. Thus, for the purposes of current study, the calculation has been made which converts the goal (stated in terms of pounds of pollution per thousand pounds of fuel) into an equivalent goal which could be stated in terms of total pounds of pollutant deposited by the airplane in a given landing/takeoff cycle. These goals are shown in figure 36.

DESIGN CRITERIA

Engine emission values
g pollutant/kg fuel

	CO (idle)	HC (idle)	NO _x (T.O.)
JT9D (measured)	58.1	15.4	42.0
EPA standard (1979)	10	2	13
ATT _{SOW} (goal)	40	8	3
G.E. (estimate) ATT 1	40	7	11-15
P&W (estimate)	30	5	12
TAC _{SOW} (goal)	20	4	10

SELECTED APPROACH

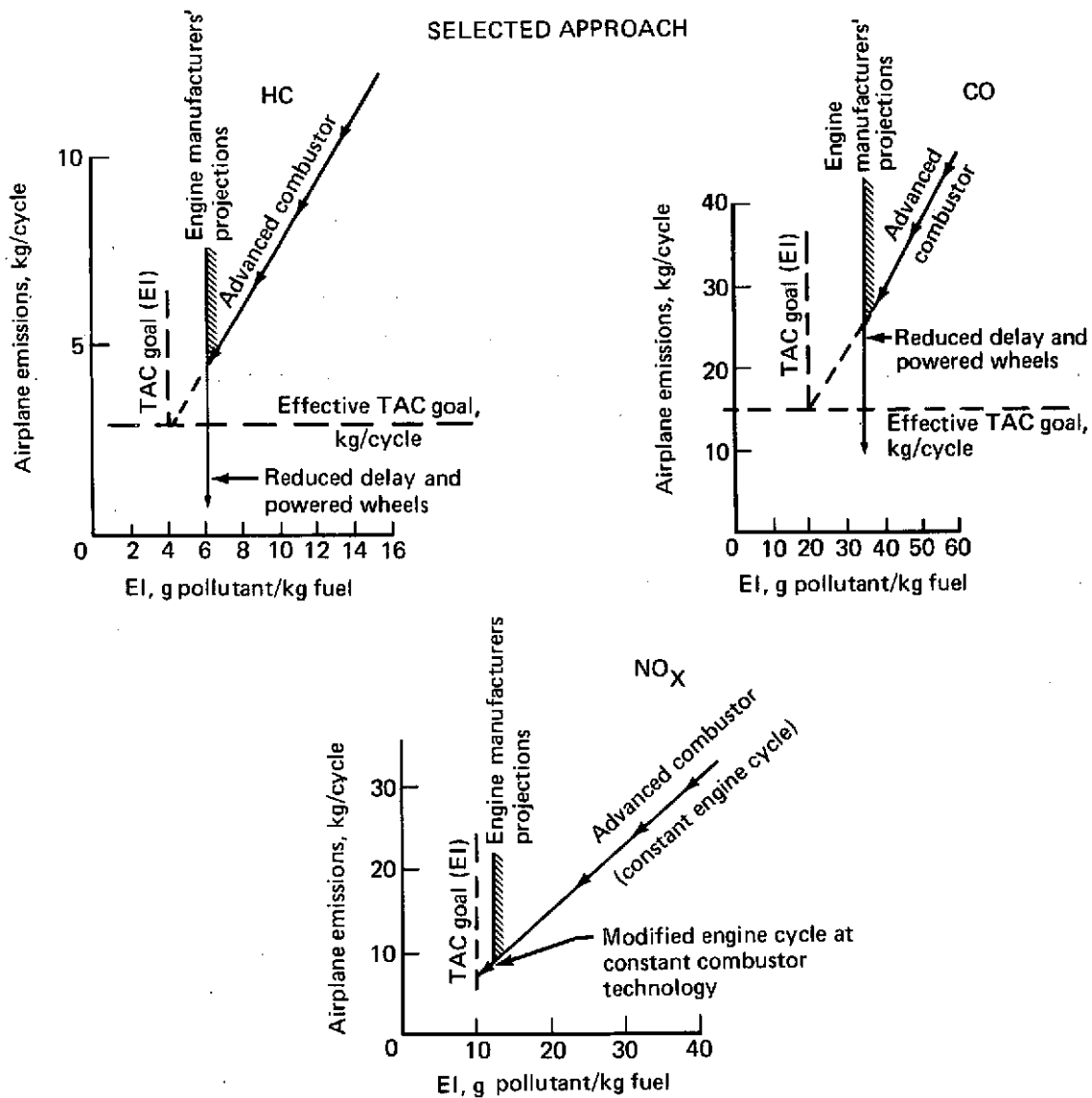


FIGURE 36.—TERMINAL-COMPATIBLE FEATURES—REDUCED EMISSIONS

The approach adopted then, to achieve the contract HC and CO goals was to utilize the advanced combustor but in addition to consider either improvements to airport ground delay or use of an airplane configured "powered wheel." In the case of oxides of nitrogen, the manufacturers' projections and the contract goal are discrepant by only a small amount. Furthermore, neither reduced delay or powered-wheel operations have much impact on oxide of nitrogen pollutant tonnages. In this case then, a change was made to the engine cycle to reduce overall pressure ratio as a means of further constraining the NO_x emissions to the contract goal.

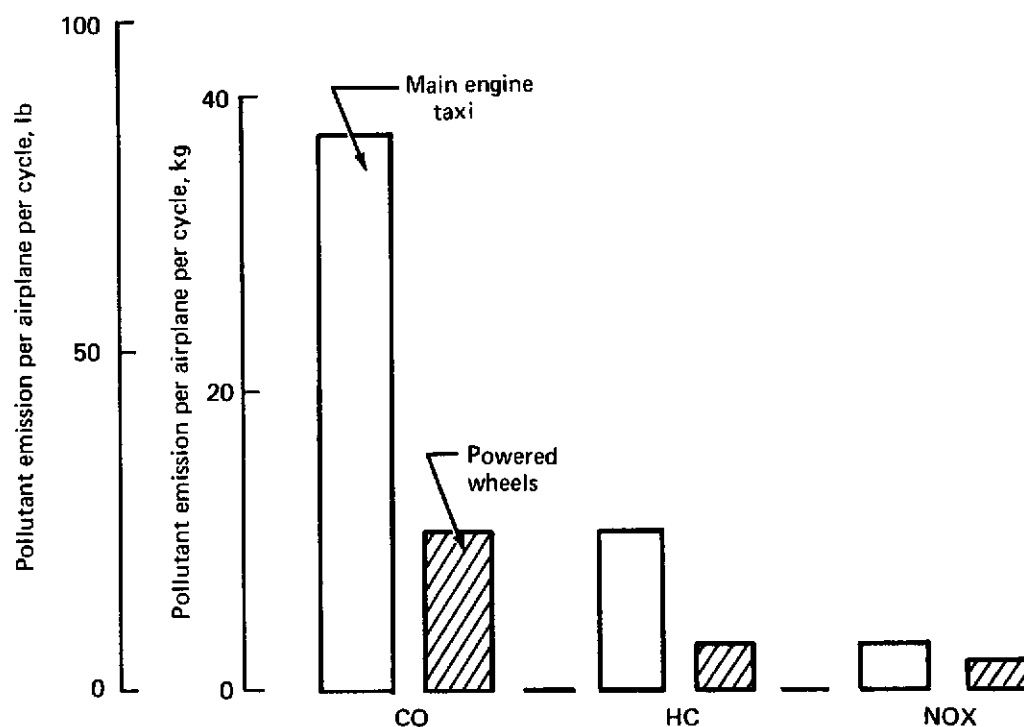
Several areas of design uncertainty exist with respect to the approach taken. These include the fact that most of the projections of advanced combustor technology are based on small-scale combustor models. The current state of the art is such that the scaling of these models to full-size engines is not always predictable. Furthermore, some of the design modifications proposed have been looked at in terms of separate improvements to either CO/HC or to NO_x levels. In many cases, when an improvement is made to one or the other of these quantities increased levels of the other are often inadvertently realized. Design uncertainties associated with the use of the powered wheel will be discussed in the next section. Since the future operating fleet will not consist of TAC airplanes alone, but rather will include varying levels of existing or other advanced aircraft types, there is some risk associated with assuming improvements to the TAC airplane which could affect reduced congestion can be counted upon to achieve reduced emissions.

6.3.5 Powered Wheel/Secondary Power System Modifications

One way to decrease the quantity of undesirable airplane-engine emissions in the terminal area is to decrease the fraction of the time during which the engines are running. This motivation is quantified in figure 37. This was made possible in the TAC airplane by putting motors on the airplane's wheels, powered from the auxiliary power unit (APU), so that the main engines could be shut off during taxi operation. This has a large effect on the emission of carbon monoxide and unburned hydrocarbons, since they are mainly produced by low-thrust, low-efficiency engine settings, as characterized by taxi operations. Secondary advantages of powered wheels include lower total fuel consumption and elimination of the need for tugs to back airplanes away from gates.

Since the APU power must be increased to power the wheels in addition to supplying the normal airplane loads, it was decided for reasons independent of emission reduction, to integrate the larger APU into the airborne secondary power system (in the baseline airplane, the APU was only used on the ground). This caused a substantially larger APU size requirement but removed the burden of supplying anti-icing power from the main engines, allowing lower power settings during descent, giving less noise and less auxiliary drag requirements. This in-flight APU use is not an essential part of the powered-wheel concept; alternative anti-icing means may be preferable for some airplane configurations.

MOTIVATION



SELECTED APPROACH

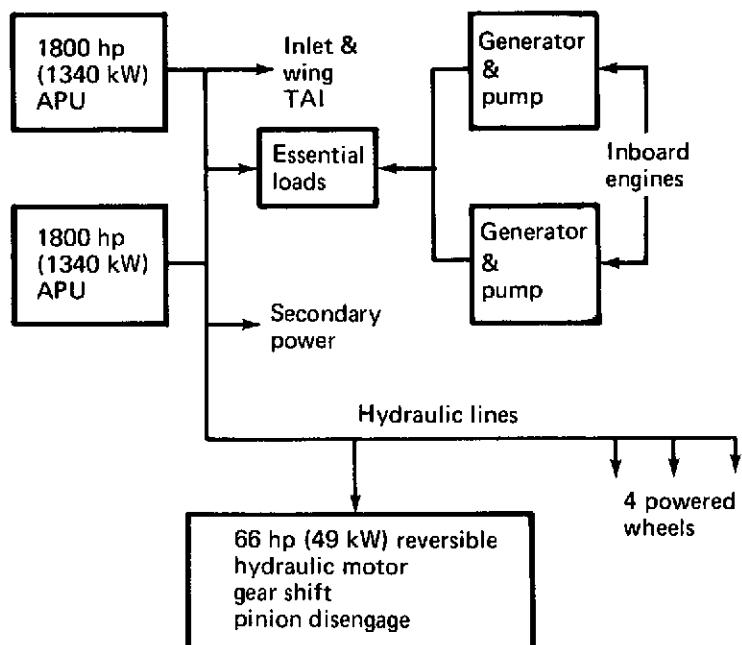


FIGURE 37.—TERMINAL-COMPATIBLE FEATURES—APU/POWERED-WHEEL DESIGN

Redundant power requirements were met by using two APUs (see figure) to supply all anti-icing power, all on-the-ground power, and the bulk of the in-flight power, with electrical generators and hydraulic pumps on the two inboard engines supplying additional channels of safety-of-flight essential loads. Electrical and hydraulic power lines from the outboard engines (placed near the wing tips in the TAC airplane for tip-vortex control) were eliminated, and outboard engine pneumatic ducting reduced to the size needed for starting air to the outboard engines. The APUs have sea-level ratings of 1340 kW (1800 hp) each; this capacity was set by the anti-icing requirement.

The powered wheels were required to move the airplane at 15 kn forward and 5 kn backward. Typical resistance forces at these speeds are 2% of gross weight, giving a power requirement of 49 kW (66 hp) for each of four driven wheels (at least four of the eight main gear wheels must be driven, for reasons of mechanical symmetry). Hydraulic motors were chosen to drive the wheels because of their lower weight and volume relative to electric and pneumatic motors.

The highest torque requirement occurs at zero speed, rather than maximum speed. This is due to the deformation of the tires of a parked airplane persisting for several revolutions under cold conditions, requiring a large breakaway force. Allowance of 6% of gross weight for this effect plus 2% for ramp slope covers essentially all situations. If the wheel motors were sized for this torque at low speed, then run at the maximum speed required without a change in gearing, excessive power would be required. A mechanical gear shifting mechanism was provided for load matching; alternatives include multiple motors switched in and out, and variable supply pressure.

The wheel drive mechanism must be disconnected during landing and takeoff and engaged smoothly during taxi (prior to shutting off the main engines after landing) and at rest. Mechanically engaging and disengaging a pinion with the wheel-ring gear was chosen over various clutches as leaving the minimum inertia attached to the wheel, an important factor during landing spinup.

Reversing is by external valving of the flow to the hydraulic motor, to avoid further mechanical complexity at the wheel. Mounting of the wheel-drive mechanism within the wheel along with the brakes requires considerable redesign of the wheel. A combination of increased tire diameter, lower tire-aspect ratio, and greater wheel assembly width is necessary to accommodate the mechanism. The wheel configuration was changed so that both brake maintenance and tire changing are still easy.

Each of the design choices concerning the wheel-drive mechanism was somewhat arbitrary; other combinations might prove to be feasible also. However, the weight penalties and wheel configuration problems of the approach chosen are typical.

6.3.6 Increased Ground-Deceleration Capability

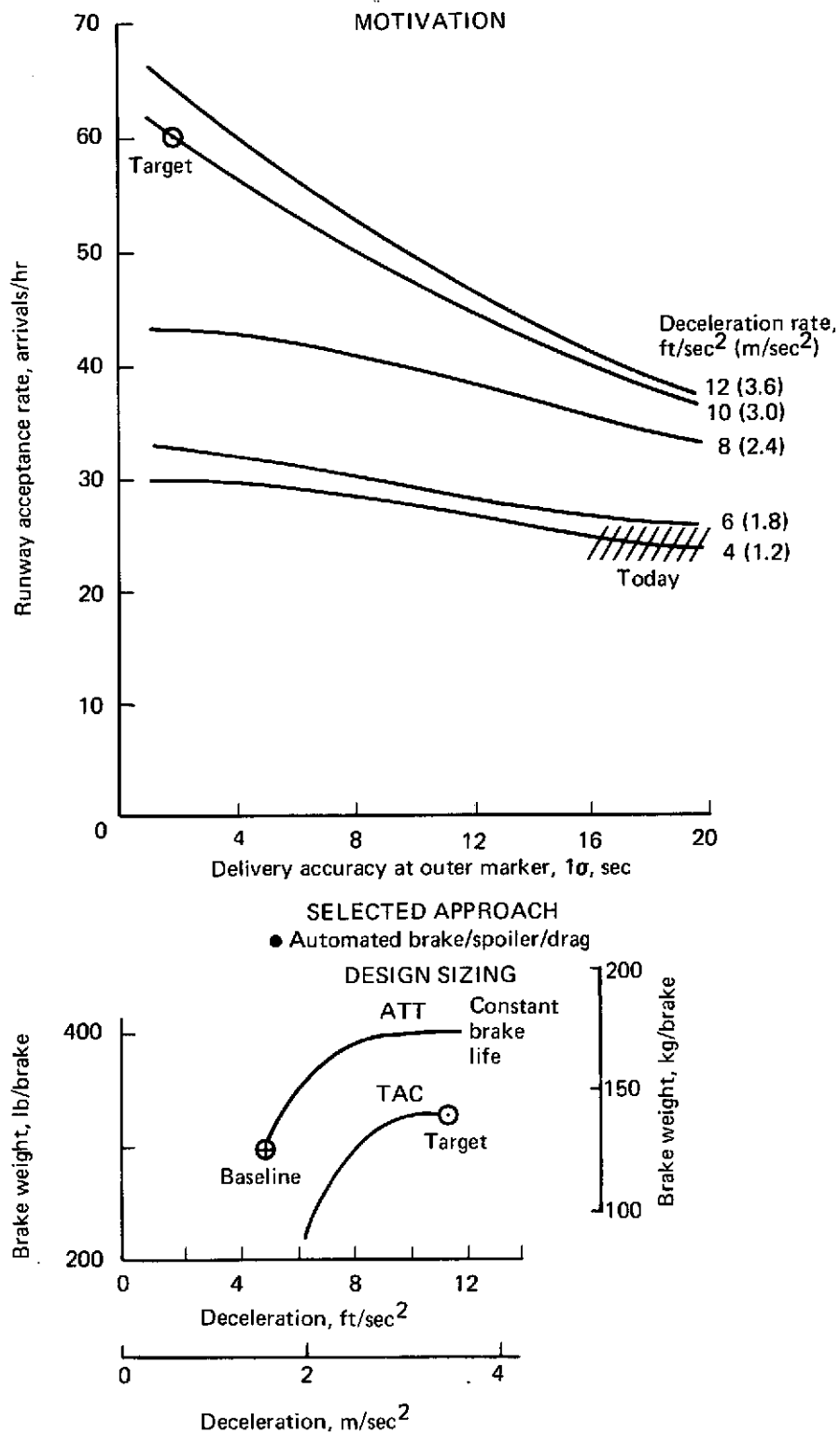
Motivation for improving ground-deceleration levels is shown with the aid of figure 38. Note the impact on runway acceptance rate of improved outer marker when ground deceleration rates are varied parametrically between current levels on the order of 4 to 6 ft/sec² up to projected levels of 10 to 12 ft/sec². Also note the potential improvement, assuming that some of the other design parameters affecting runway acceptance rate are also achieved, of about 100%.

A number of design alternatives exist to achieve the increased deceleration rates. These include improving airplane thrust reverse, ground-drag levels, and braking characteristics. An alternate approach is the use of external stopping devices such as nets or wires but this option was not considered for the current contract since it is primarily a ground facility system.

A number of design criteria were established to guide the modifications to the TAC airplane. A goal of 10 to 12 ft/sec² was established on the basis of the runway congestion studies and an additional constraint requiring less than 0.1 g/sec change in deceleration (i.e., jerk) was also established based on previous Boeing studies of levels which would not arouse passenger objection. A design goal was set that these deceleration levels be achievable under wet runway conditions. The ability to handle icy runways was not required since most major airports today have ice-removal capability. The decision was made to require that deceleration rates be achieved without a change to the current airplane certification procedures which do not give credit for deceleration forces produced by thrust reversers.

The design approach selected included improving the capability of the baseline ATT braking system by adding sufficient additional brake material to achieve no degradation of brake life relative to the ATT airplane. This approach also required introduction of an automated braking system in order that full utilization could be obtained of the potential brake retarding action. In addition, the automated braking system was deemed desirable so that application and disengaging of the braking system could be affected smoothly in order to achieve the desired deceleration levels without exceeding jerk levels in excess of estimated passenger tolerance values. It should also be noted that in achieving the desired ground deceleration, use was made of the increased aerodynamic drag available by redeploying the steep descent drag brakes. In addition, it should be noted that the braking requirements for the TAC airplane were somewhat less initially than those for the ATT airplane because of the reduced approach speeds.

Some of the design risk areas inherent in the modifications proposed for the TAC airplane include the following: low aspect ratio tires were assumed in order to enable additional room for the increased amount of braking material required; (2) questions exist concerning potential brake/landing gear vibration problems because of the continual increased high deceleration rates;



**FIGURE 38.—TERMINAL-COMPATIBLE FEATURES—INCREASED
GROUND DECELERATION RATES**

(3) A final major uncertainty concerns tolerance levels of the passengers and the safety aspects of employing the high deceleration rates continually under low visibility, wet runway conditions. This will be discussed in a little bit more detail in section 3.7 in conjunction with the high-speed turnoff capability.

6.3.7 High-Speed Turnoff

Motivation for providing high-speed turnoff capability for the TAC airplane is not independent from the higher deceleration levels discussed in section 6.3.6. Figure 39 illustrates in terms of runway acceptance rates a potential improvement associated with increased exit velocities. The reader should note that the values shown are dependent not only upon the specific exit geometry assumed but again, are also dependent on achieving improvements to such other factors affecting runway rates as reduced air-to-air separation and others.

A number of potential design impact areas which are affected by the requirement for high-speed turnoff were identified. These include the ability to achieve sufficient traction from the nose-wheel steering system and this in turn is dependent upon the fore and aft weight distribution of the airplane and also the ground-surface conditions of the runway itself. If operations are not to be degraded by low visibility weather, then additional guidance information and improved cockpit displays were judged to be required. Again, the airplane configuration and landing-gear design are affected but particularly the question of passenger acceptance of the high-speed turnoff maneuver was a principal concern.

Several design criteria were established to which the TAC airplane design improvements were developed. The key item to point out concerns pilot acceptance which in evaluating the potential introduction of high-speed turnoffs to existing airline operations would be a key ingredient. Pilots have frequently voiced concern that the success of the high-speed turnoff maneuver would be dependent on providing the pilot adequate guidance and notification as to location of the high-speed runway exits and the path for him to follow for ground movement. An important design criterion also was the requirement for essentially all-weather capability. Weather had been identified as a factor which currently leads to significant levels of aircraft and airport congestion. It is particularly important that future aircraft when considered in light of projected more tightly structured airspace control procedures possess such all-weather capability.

The bottom chart of figure 39 provides an indication, in terms of side-force limitations on the airplane, of which design constraints are controlling. The figure shows simplified runway turn radius versus airplane taxi speed. Each of the lines shown essentially represents a fixed level of centrifugal acceleration. Studies conducted under task III have shown that the landing gear already selected for the ATT airplane can achieve the design high-speed turnoff without major

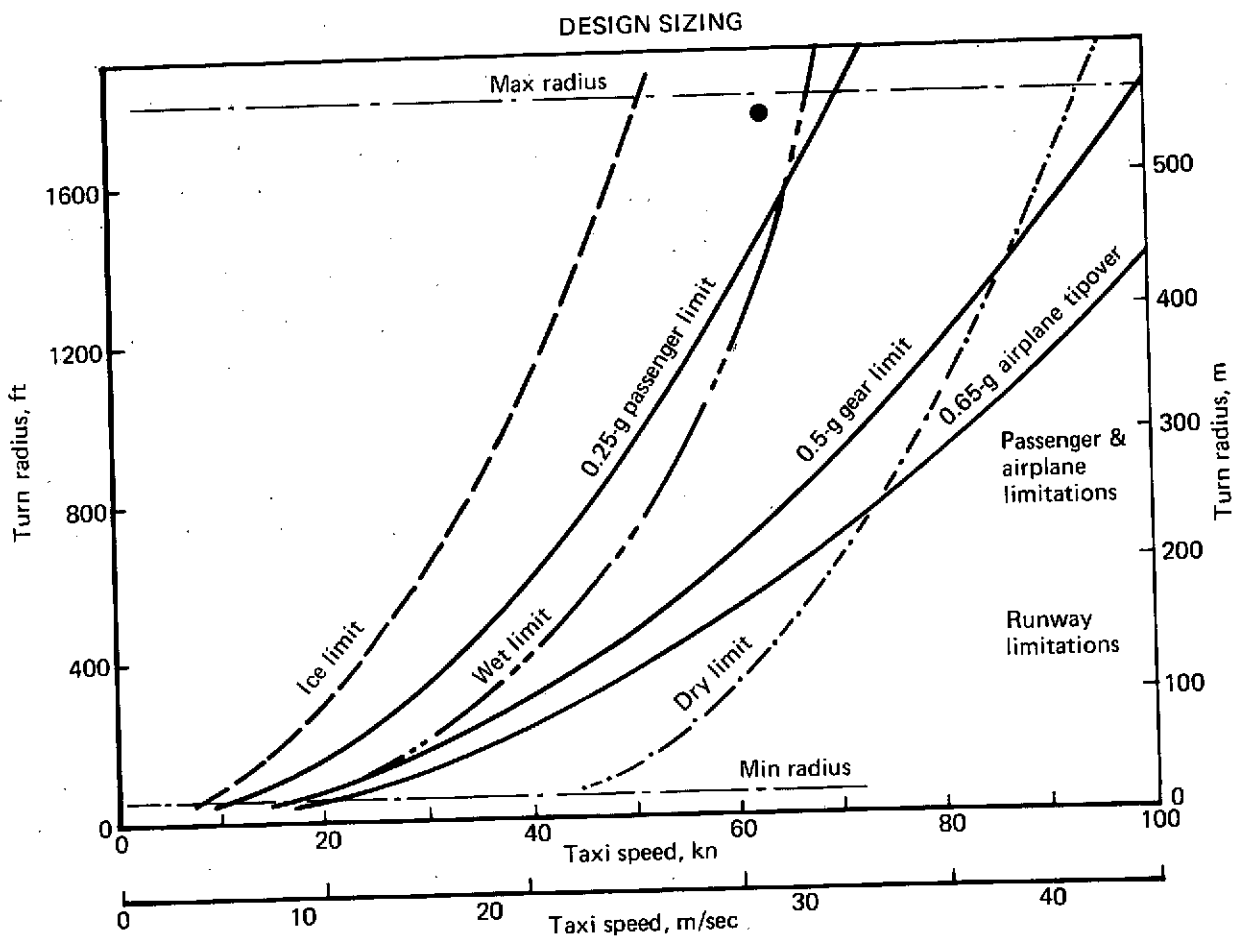
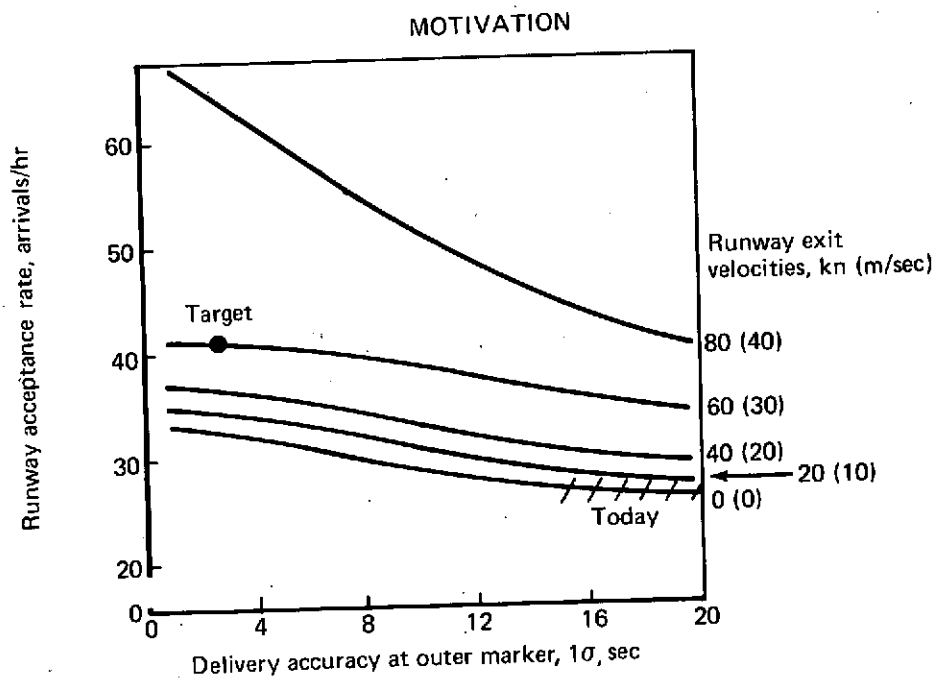


FIGURE 39.—TERMINAL-COMPATIBLE FEATURES—HIGH-SPEED TURNOFFS

modification to the airplane. In fact, the major operational limit to the airplane was determined to be passenger tolerance. The figure also distinguishes the specific turn radius of 550 m (1800 ft) which is consistent with a recommended high-speed turnoff runway geometry as specified by FAA airport runway design guidelines. The data indicate that a 31-m/s (60-kn) turnoff is consistent with all the design constraints and that sufficient traction can be achieved to support this level of acceleration for runway conditions ranging from dry to somewhere between wet and icy.

Additional design changes required of the airplane included modifications to the avionic system which would provide sufficient guidance to the pilot for ground operations so that a skilled pilot could execute high-speed turnoff with equivalent confidence in safety to today's ground airplane operation.

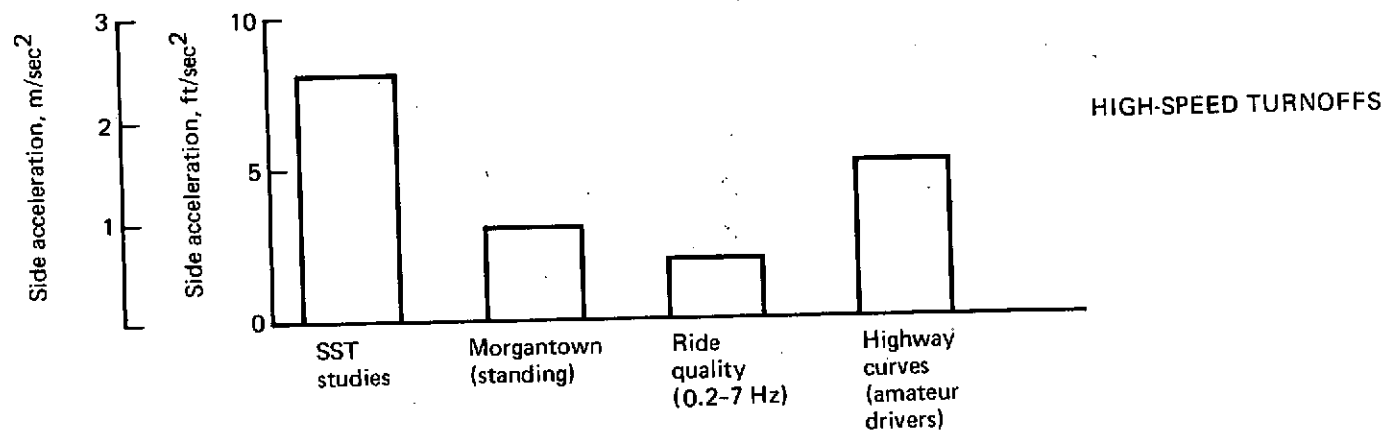
Some design risk is associated with employing the proposed TAC airplane for high-speed turnoff use. The principal risk appears to be achieving both passenger and pilot acceptance without causing undue concern. This concern is similar to that discussed previously for the high deceleration rates. Figure 40 provides indication based on data reviewed and accumulated under the task III effort concerning traveler tolerance in various transportation modes to linear and side accelerations. The data are not as detailed or as directly applicable as would be desired. They include information accumulated in assessing the ground-ride qualities of the Boeing SST airplane and data developed to support the Boeing personal rapid transit system developed for experimental use in Morgantown, West Virginia. This, of course, is a ground system. Nevertheless the test data shed some light on passenger tolerance, to the expected forces. In addition, experience associated with the automatic braking system which has been offered on some versions of the Boeing 737 airplane have also been incorporated. In sum, the results show that the estimated goals do not appear infeasible from the point of view of passenger tolerance. However, it is recognized that more consistent and directly pertinent data would be required to demonstrate this point.

Figure 41 is included to give a rough indication of the relative geometry for the FAA recommended high-speed turnoff exit in relationship to current runway taxiway geometries. The figure shows a blown-up version of such geometry for LAX and ORD airports. Superimposed is the recommended FAA high-speed runway exit.

The conclusion cannot yet be drawn that such runway geometries are consistent with the airplane requirements for high-speed turnoffs since the kinematics of such a maneuver have not been addressed in detail in the current study. In particular, questions concerning disposition of the aircraft after having successfully executed the high-speed turnoff still remain. The question simply is, is there sufficient ground space for the airplane to complete its deceleration to moderate taxi speeds after having exited the primary runway? The figure does show, however, that at least

Target

Today



Target

Today

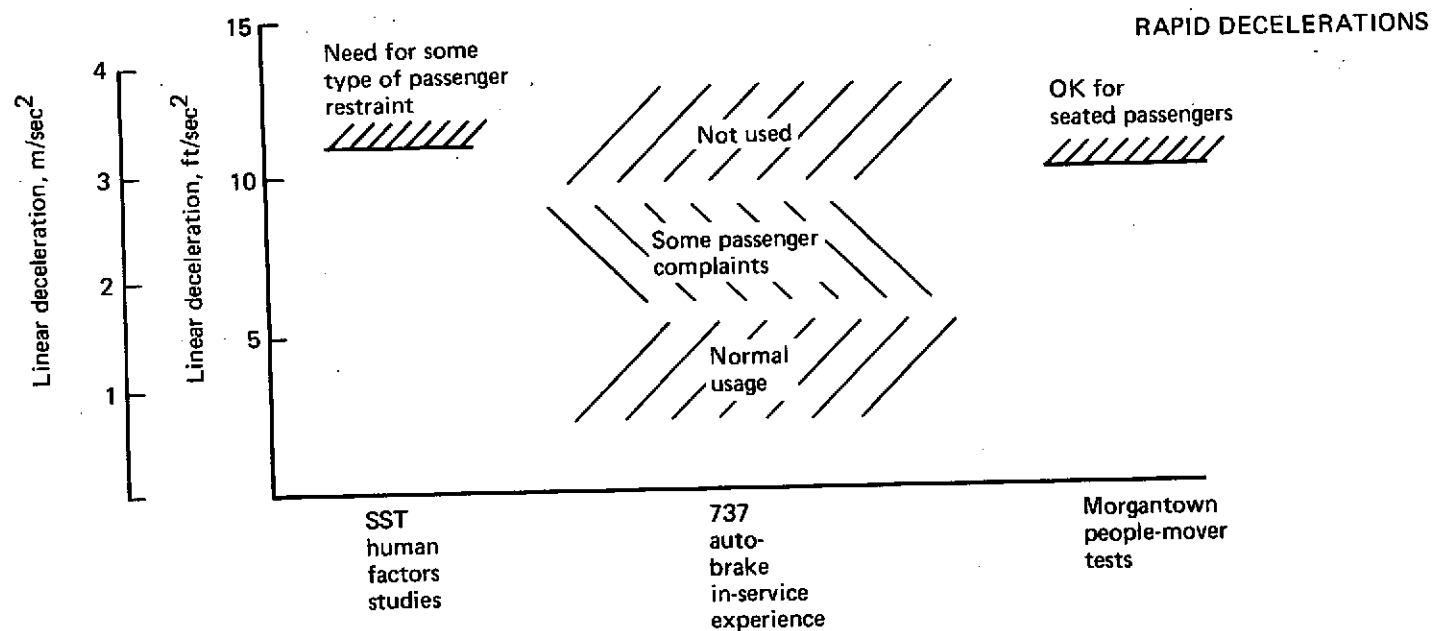


FIGURE 40.—PASSENGER TOLERANCE DATA

- Existing
runways
- High-speed exit
requirements

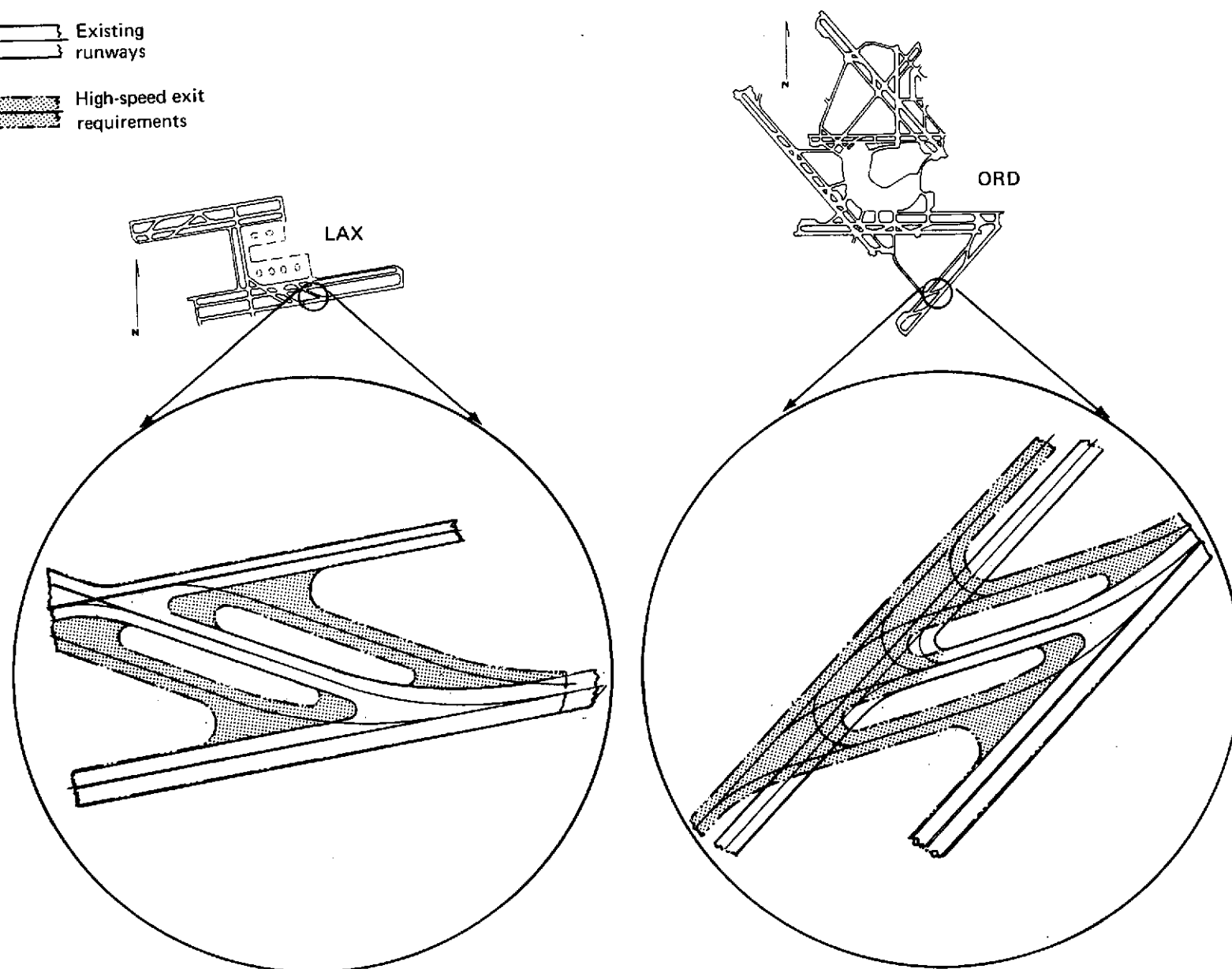


FIGURE 41.—PRELIMINARY LOOK AT HIGH-SPEED EXIT GEOMETRY

for LAX the runway taxiway geometry itself is not inconsistent with the FAA recommended high-speed turnoff although some modification would appear to be required with the runway geometries at O'Hare airport.

6.3.8 Avionics System

To achieve the TAC goals the airplane avionics system, figure 42, must interface with the ATC system in such a way as to take full advantage of ATC procedures designed to provide an efficient, high-capacity, quiet air transportation system. This interface requires accurate time-referenced area navigation capability, and air/ground data link integrated with the navigation and display elements, and the airborne elements of a universal surveillance system. For safe operation, these functions must be integrated with the flight control system and with crew displays and controls in such a way that the crew workload is kept to an acceptable low level while the crew is kept clearly and unambiguously informed of the total navigational and operational situation. For economic reasons, the acquisition and maintenance cost of such a system must be kept within bounds by integration of the navigation, flight control, communication, and display systems in a way that gives the required capability and redundancy with minimum total equipment, and by the inclusion of adequate automatic monitoring of subsystem status and performance.

All these goals were met, in theory, by the avionics system on the baseline airplane, although much development remains to establish operational feasibility. The TAC airplane design impacts these requirements in two ways. First, configuration changes to the airplane may require matching changes in the avionics system; for example, appropriate channels and readout devices must be available to control and monitor the operation of vortex dissipators, auxiliary drag devices, and changed numbers of APUs and main engines. These changes only affect size and quantity, and do not require technological advances.

Second, the operational procedures to be used to decrease noise and congestion place more stringent requirements on the avionics/pilot combination. Specifically, the two-segment steep descent, the low-visibility landing, the rapid deceleration and the high-speed turnoff, for minimizing runway occupancy time, individually impose requirements which can be met by little or no change from the baseline avionics systems. But taken together, as key elements which must be consistently combined in rapid succession under essentially all-weather conditions, they give much greater emphasis to the requirement for a carefully developed combination of automated functions, pilot displays, and pilot operations. The impact on the avionics system cost and weight are minimal; the same basic hardware will be used, with the probable addition of an additional sensor for surface guidance. However, to arrive at the decisions as to the exact functions performed by that hardware, the content and format of displays, and the operations left to the pilot, will require extensive research.

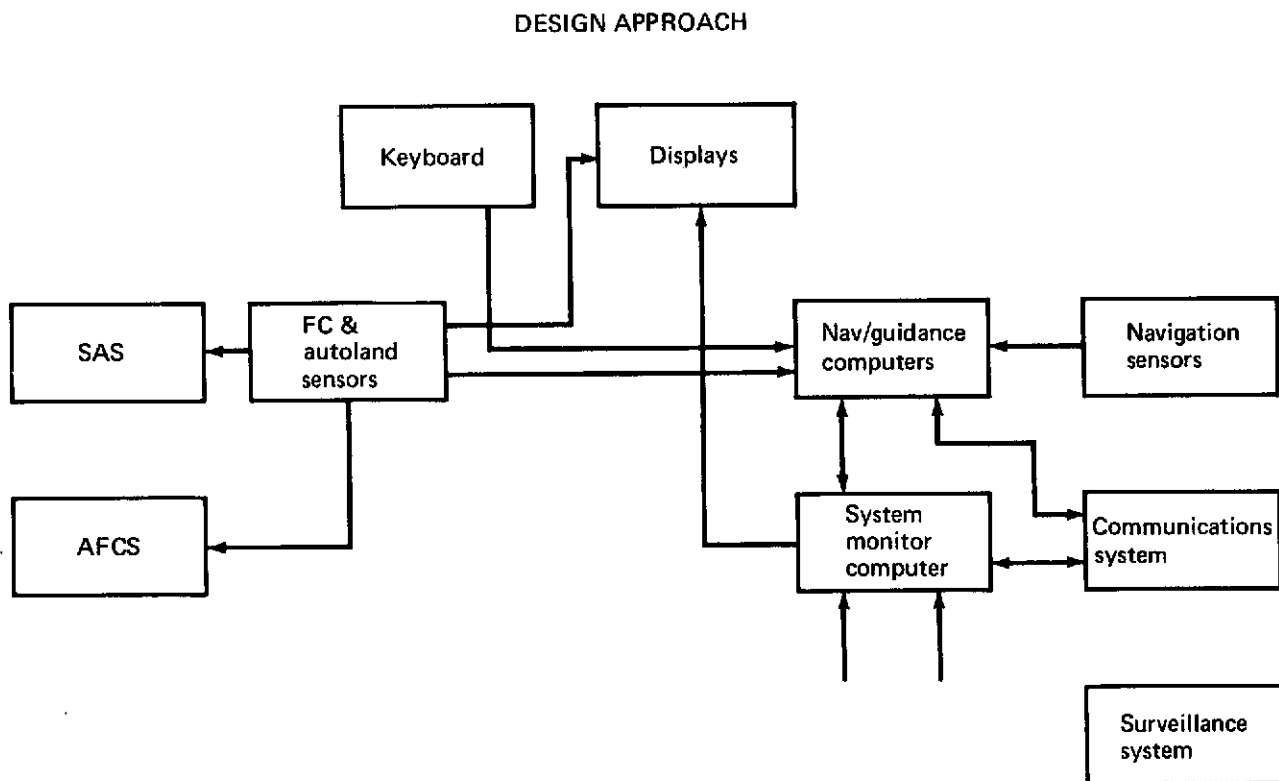
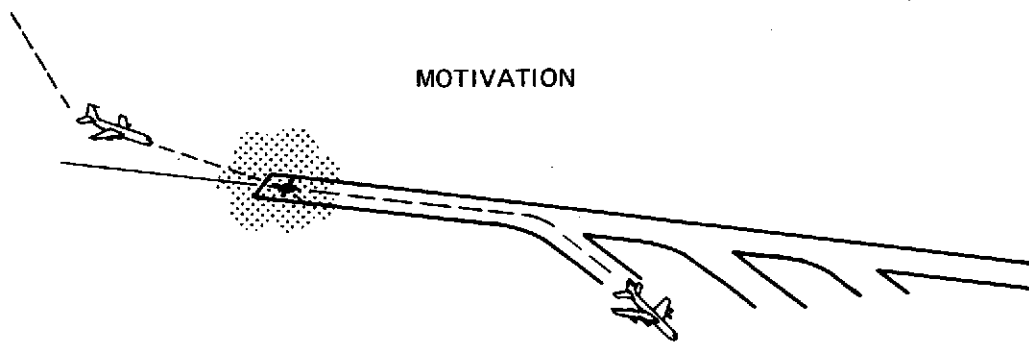


FIGURE 42.—TERMINAL-COMPATIBLE FEATURES—AVIONICS IMPLICATIONS

The baseline avionics system is a highly integrated digital system. Sensing and computing elements are grouped by redundancy requirements including: quadruple safety-of-flight stability augmentation systems, triple AFCS, dual navigation and guidance, and a single-thread system monitor. Basic inertial data for all applications is from a strapdown system. Navigation data is from a differential omega system enroute and from the MLS in the terminal area. All normal communication is via a data link. Extensive use is made of programmable CRT display system elements for flight director, navigation, and system status applications. An extensive system monitor gives system status for critical operations and failure and trend data for maintenance.

6.4 RTOL AIRPLANE CONFIGURATION

One requirement of the current study involved estimating the impact of reconfiguring the TAC airplane to a 1524-m (5000-ft) takeoff and landing field-length capability. To fulfill this requirement several additional studies were undertaken. First, an assessment of potential propulsive lift design concepts was made in order to understand the best means of achieving a 1524-m (5000-ft) field-length capability. Second, a particular evaluation was made of an overwing engine installation. This latter concept offered not only potential field-length reduction by means of thrust deflection and boundary layer control (upper surface blowing) but also because this concept provides potential noise improvement due to wing shielding. Finally, but somewhat in parallel, a review was made of the potential marketability and attractiveness of long-haul aircraft with the RTOL capability.

The results of each of the above considerations are discussed separately in this section. As these results will show, none of the more innovative high-lift concepts were judged to be competitive with the conventional mechanical flap system. Thus, the conventional flap system was in fact used in configuring the TAC-RTOL airplane. The penalty for achieving 1520-m (5000-ft) field-length and the resulting implications for takeoff noise are shown.

6.4.1 Assessment of Propulsion Lift Concepts

It was not judged feasible to develop competitive propulsive lift design configurations within the scope of the present contract. Instead advantage was taken of previous Boeing studies wherein such designs were developed in considerable detail. For the most part, these concepts were configured for application to short-haul aircraft. Several Boeing aircraft had been configured to use such propulsive lift concepts as the augmentor wing, externally blown flap, and the powered jet flap. These configurations were studied previously by Boeing against a conventional mechanical flap airplane which was a modified 727 airplane, altered to provide 1219-m (4000-ft) takeoff field-length capability. The previous study airplanes were configured to ground rules that were

somewhat different from those used for the ATT and TAC airplanes. A payload of 120 passengers was considered over a design range of 1852 km (1000 nmi). The airplanes were, however, designed with a noise constraint in mind, in particular noise levels were targeted to achieve between 80 to 85 EPNdB at a 609.6-m (2000-ft) sideline distance. This noise goal is not inconsistent with the noise levels targeted for the TAC airplanes. All of the aircraft were configured to achieve between 3000-and 4000-ft takeoff field lengths.

The augmentor wing (AW) concept diverts all of the engine fan airflow to independent plenum chambers within the wing. The air is then in turn fed to the high-aspect ratio flap nozzles. The engines were pylon mounted and located for minimum-cruise drag. Such a system offers a significant component of thrust in a lift direction which is augmented by use of the ejector nozzle contained in the flap system.

The externally blown flap (EBF) airplane configuration utilized a high-bypass ratio engine with a low fan pressure ratio to reduce jet flap interaction noise. The engine fan exits were located at the leading edge of the wing with a vertical position close to the wing in order to achieve high-flow turning efficiency without impinging on the leading edge flap system or introducing significant scrubbing losses in cruise flight.

The powered jet flap (PJF) airplane design is similar in concept to that of the augmentor wing where air is ducted from the primary engines into plenums located in the wing structure. This air is then exhausted over the wing flap system. The concept does not use the elaborate jet flap construction associated with the augmentor wing but rather employs a simpler single airfoil section which acts to promote efficient flow turning rather than complete thrust deflection.

Figure 43 presents the results of that study showing weight, aerodynamic, and propulsive penalties relative to the baseline mechanical flap system. As seen in the figure, both the augmentor wing and power jet flap configurations behaved in a similar fashion and establish similar levels of penalty. These amounted to on the order of 5% increase in OEW compared to the external blown flap installation which incurred a penalty on the order of 20% to 25% OEW increase. The three propulsive lift concepts showed total range factor penalties of the same order of magnitude being between 25% to 30% decrease in range factor. Losses for the augmentor wing and powered jet flap were evenly divided between the propulsive losses (pressure drop) incurred because of the internal flow ducting through the wing and aerodynamic losses incurred as a result of increased wing thickness and resulting cruise-drag increases. In contrast, the relative propulsion losses of the external blown flap are considerably less than the aerodynamic losses which are incurred largely as a result of the high-bypass ratio integration with the wing aerodynamic flow field. The reduced propulsion losses reflect the improved SFC of the high-bypass ratio engine.

Figure 44 gives a rough estimate of the potential penalty to takeoff gross weight to the TAC-RTOL airplane if it were outfitted with either of the three previously described propulsive lift concepts relative to a mechanical flap arrangement. The data do not pretend to represent a detailed assessment. Rather they give a rough indication of the impact of the propulsive lift concepts if similar levels of weight, drag and SFC penalties were incurred as those shown above for the design study accomplished on the smaller, shorter-range airplane. The data show that penalties on the order of 25% to 50% increase in gross weight would be incurred. This is without taking into account the fact that the basic TAC airplane is intended for Mach 0.9 cruise, whereas the cruise Mach number of the previous STOL-type aircraft was in the neighborhood of 0.8 Mach number. Increased cruise speed requirement of the TAC airplane could be expected to considerably increase such problems as integrating the high-bypass ratio engine installation or utilizing inordinately thick wing sections.

In view of the penalties associated with the propulsive lift concepts studied, future investigations might consider more limited means for achieving high-lift coefficients, such as limited blowing or suction, for improved boundary layer control. Mechanical complexities will still be involved in this approach, however.

6.4.2 Overwing Engine Installations

In the past several years, considerable research and development effort has been expended on the so-called overwing engine installation concept. Potential advantages of this concept are shown in figure 45. Basically, shielding of aft-radiated engine noise by the wing is possible for a nacelle with its trailing edge well forward of the wing. An additional potential for the overwing installation also is relevant to the requirement for reduced field lengths. This includes utilizing the Coanda effect for entraining the jet air around the wing flap to promote thrust deflection and improved lift coefficient.

Data from a previous Boeing study for two four-engine-on-the-wing airplanes, each designed to a given payload/range are shown in the figure. The over-wing installation showed a 1% weight advantage, a 1% cruise SFC penalty and a 10% cruise-drag penalty relative to the over-wing installation. The increased fuel usage for the over-wing installation existed in spite of the reduced internal losses associated with the acoustic treatment. These losses were incurred as a result of wing scrubbing losses due to the engine exhaust upon the wing during cruise. Weight savings were realized for the over-wing installation in spite of the additional heat resistant material provided on the upper surface of the wing. Strut and acoustic material weight benefits were the reason. The principal disadvantage of the over-wing installation was a minimum of 10% cruise-drag penalty based on wind tunnel tests of similar four-engine configurations. These tests were conducted at Mach 0.8 cruise conditions and were carried out on a four-engine installation with conventional outboard

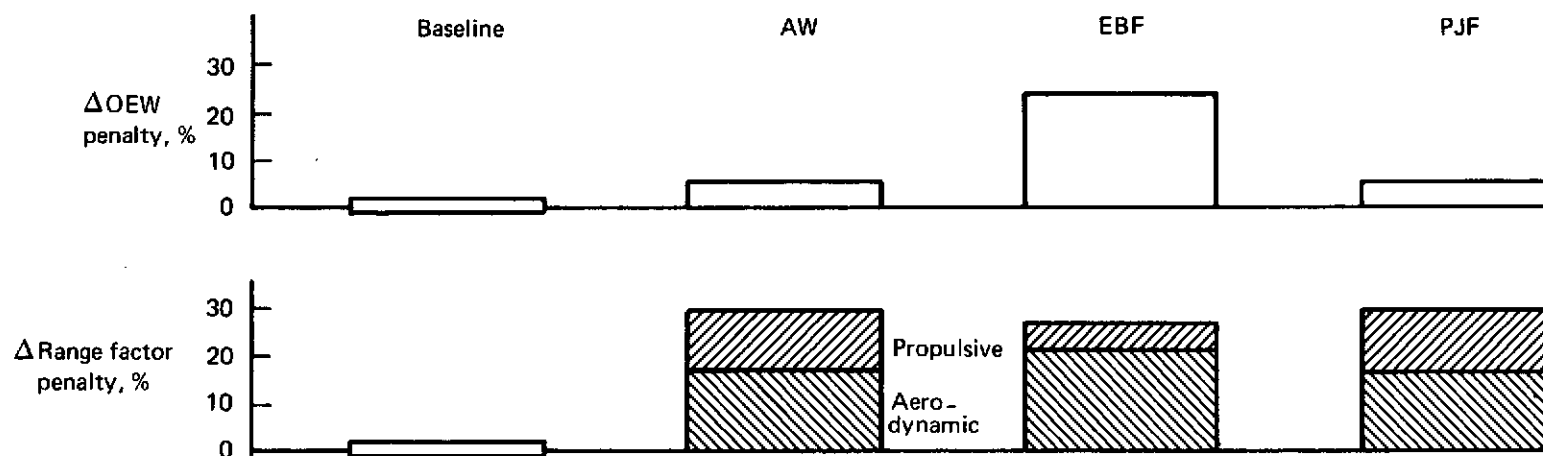


FIGURE 43.—ASSESSMENT OF PROPULSIVE LIFT CONCEPTS—RESULTS FROM PREVIOUS STUDY

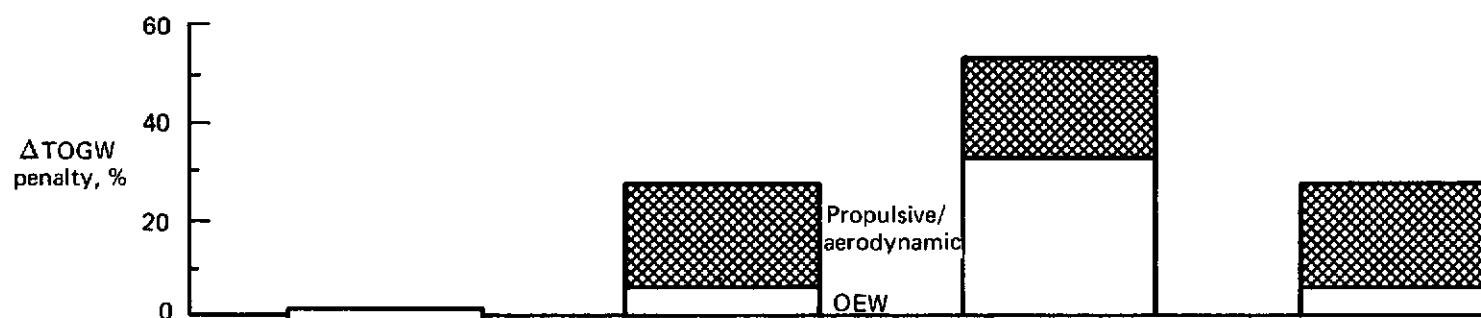
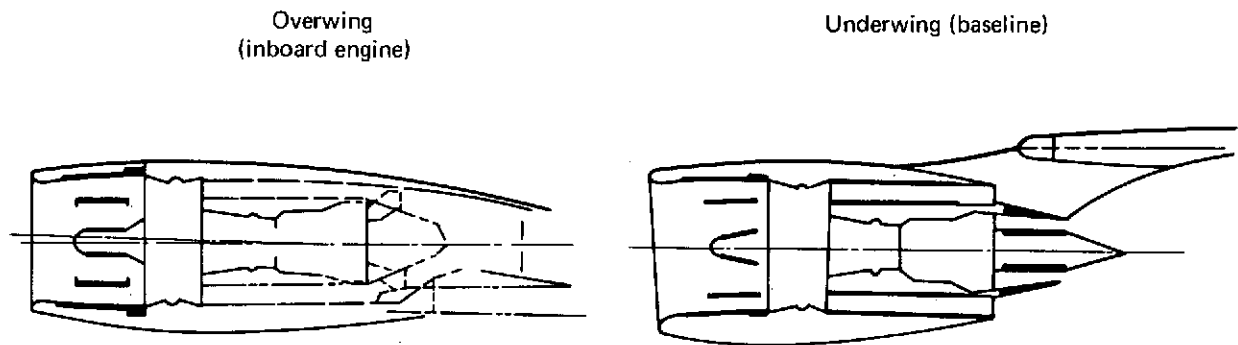


FIGURE 44.—ASSESSMENT OF PROPULSIVE LIFT CONCEPTS—ESTIMATED IMPACT ON TAC AIRPLANE

1. Potential advantages of over-the-wing:
 - Noise shielding benefits
 - Aft fan noise
 - Engine core noise
 - Utilize upper surface blowing for reduced field lengths
2. Evaluation based on previous Boeing study:
 - Typical nacelle configurations designed for equal noise



Effect of:	Previous study results ^a		Estimated TOGW increment on TAC for overwing
	Overwing	Underwing	
OEW	-1%	Base	-1.5%
Cruise L/D	-10%	Base	+8%
Cruise SFC	+1%	Base	+5%
			$\Sigma + 7\%$ TOGW

^aBased on Boeing wind tunnel tests and studies of four-engine configurations

FIGURE 45.—ASSESSMENT OF OVERWING INSTALLATION FOR TAC-RTOL AIRPLANE

engine spanwise location. The wind-tunnel results showed the principal source of the drag penalty was associated with the aerodynamic interference between the outboard nacelle and the wing.

With respect to the TAC-RTOL airplane it might be expected that this drag penalty would be even higher because of: (1) The higher cruise Mach number for the current airplane; and (2) the increased difficulty of integrating the outboard engine at an extreme spanwise location in combination with the high-aspect ratio wing such as used for the TAC airplane for reasons discussed earlier.

In spite of these probable penalty increases an assessment was made for the payload/range of the TAC airplane of incremental TOGW penalties for an over-wing installation relative to a conventional four-engine underwing pylon mounted installation. These gross weight increments are also shown in figure 45. In summary, they show a minimum of a 7% takeoff gross weight penalty for such an over-wing installation. This assessment was judged to carry with it considerable risk because of the previously discussed factors and the probable increased noise level (unaccounted for in the current study) which would be achieved if significant flow turning were developed to achieve shorter takeoff-field lengths.

The conclusions reached then, *for the TAC airplane* based on this review of the more detailed airplane study were these. Under the best of circumstances the four-engine over-the-wing installation would incur a minimum of 7% increase in TOGW. This penalty would be incurred without yet paying any additional penalties for the flow turning required to achieve high lift coefficient. The TAC airplane requirements for Mach 0.9 cruise and an extreme outboard location for the outboard engine would seem to be incompatible with the requirements of a successful over-wing engine installation. The reader should be careful to avoid concluding that such an installation has no advantages, in fact, may easily be realized for a two-engine airplane configuration and particularly when such a configuration is designed for lower cruise Mach numbers.

6.4.3 TAC-RTOL Airplane Sizing

As a result of the considerations discussed in some detail in sections 6.4.2 and 6.4.3, it was concluded that the conventional underwing engine installation with mechanical flaps would be best suited to achieve 1520-m (5000-ft) takeoff field length for the TAC airplane. Such an airplane was, therefore, configured and an analysis made of appropriate engine and wing sizes in order to achieve the reduced field-length capability. The TAC-RTOL airplane configuration has been previously shown in section 6.1.

Figure 46 presents a summary assessment of the takeoff gross weight penalty incurred as a function of takeoff field length between the ranges of 2440 to 4880 m (4000 to 8000 ft). The figure also provides an indication of the impact on noise of different sizing assumptions. Considering

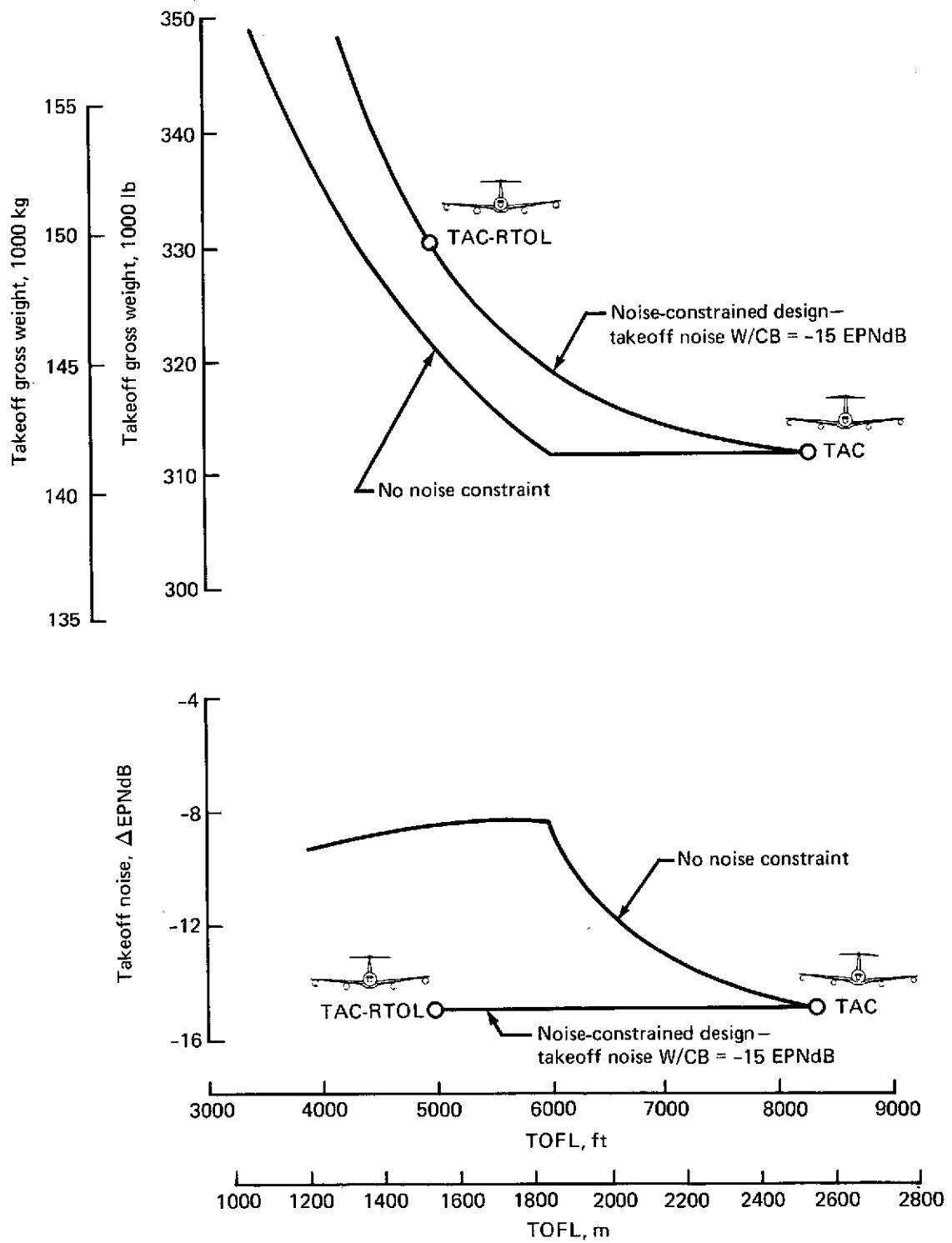


FIGURE 46.—SIZING OF TAC-RTOL

the plot to TOGW versus field length, the lower curve establishes a penalty to achieve 1520 m (5000 ft) field length on the order of 3% in TOGW. This modest penalty is achieved by allowing the aircraft to make maximum use of a high-flap setting for the ground run and takeoff climb. However, as shown in the lower part of the figure the corresponding impact on takeoff noise shows an increase on the order of six to 8 EPNdB. This is associated with the rather poor climbout gradient which would be achieved by such an airplane utilizing the relatively high-flap setting. An alternate design approach would be to utilize more modest flap setting on takeoff and add additional engine thrust to the levels required to achieve the 1520-m (5000-ft) takeoff field length. This approach retains sufficiently good climbout gradient to maintain takeoff noise at or better than the TAC airplane at its 2530-m (8300-ft) field length capability. This latter approach was assumed for the sizing of the TAC-RTOL airplane. As shown in figure 46, an incremental takeoff gross-weight penalty on the order of 6% to 7% is then paid for the takeoff field length improvement.

As a result of using the higher thrust size engine, the question was raised whether a higher bypass-ratio cycle would be appropriate. The higher bypass provides greater relative takeoff-to-cruise thrust and lends itself to improved noise levels. A bypass-ratio-five engine developed from the same parametric engine characteristics was studied and compared with the baseline bypass-ratio-four engine for several levels of noise treatment ranging from hardwall to four inlet rings with two -fan duct splitters. Results are shown in figure 47. The bypass-ratio five showed less penalty at noise levels less than about 15 EPNdB below FAR Part 36 except for approach noise which is considerably affected by airframe noise and is unaffected by engine cycle. However, at a noise level of our slightly above FAR Part 36 minus 15 EPNdB, the bypass ratio four incurred less gross weight penalty when considered in terms of a single "treated" noise index. In any event, the gross weight differences were quite small at the noise levels of interest and the baseline bypass ratio four cycle was retained for the TAC-RTOL airplane.

6.4.4 Market Analysis for TAC-RTOL Airplane

6.4.4.1 Overview

The purpose of this study was to evaluate the potential market for an advanced technology transport designed for a 5560 m (3000 nmi) range modified to provide the capability for reduced takeoff and landing field lengths. This capability would permit long-range flights to utilize small- or medium-size airports for which runway length might otherwise be a constraining factor. The study sought to determine the economic value of the short-field length capability. Implicit in the analysis is the assumption that extension of runway length in these smaller airport communities would be frustrated by community resistance to airport expansion, high land values or other well-known obstacles.

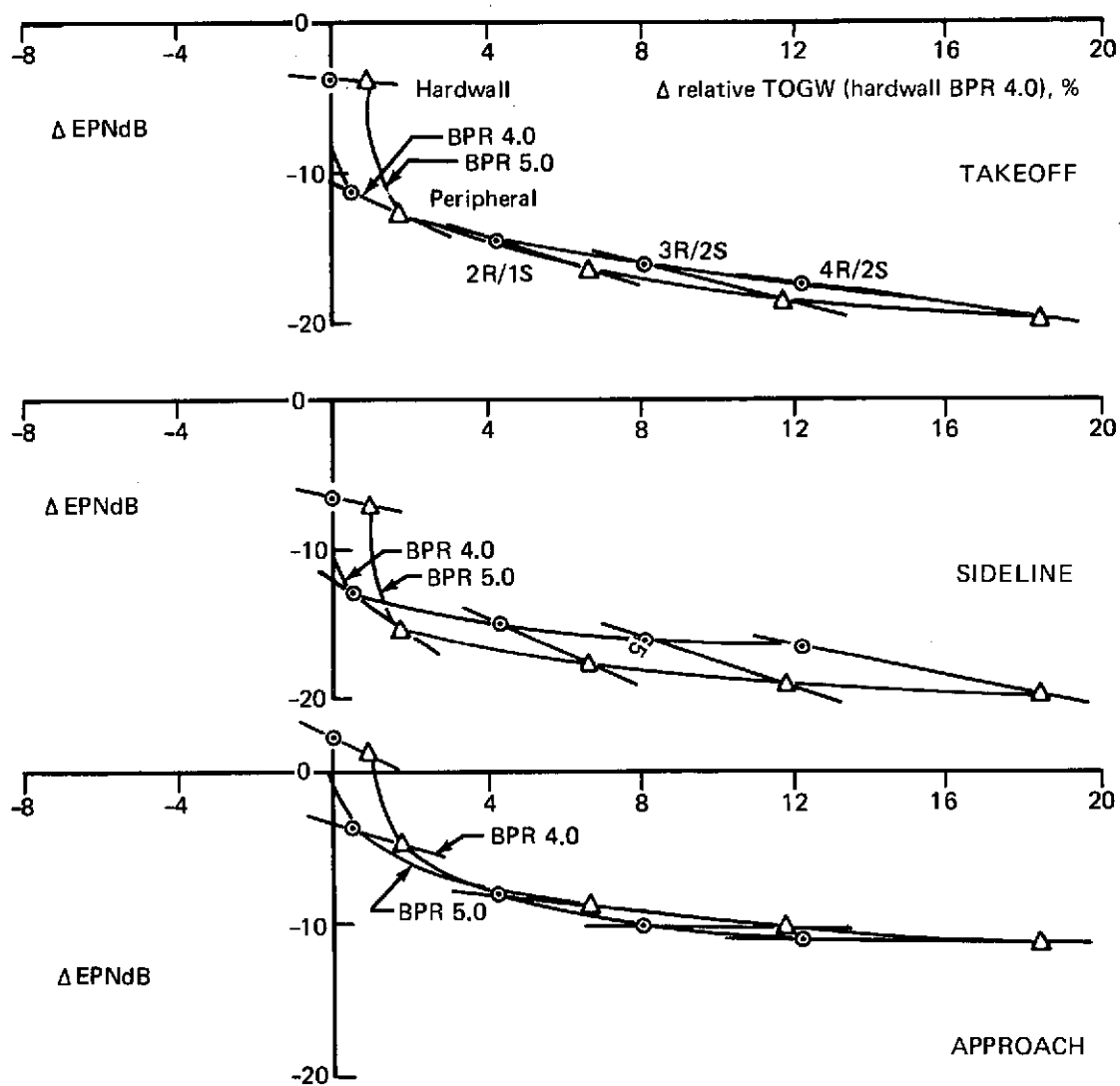


FIGURE 47.—EFFECT OF BYPASS RATIO ON NOISE/GROSS WEIGHT TRENDS

6.4.4.2 Long-Haul Aircraft Markets

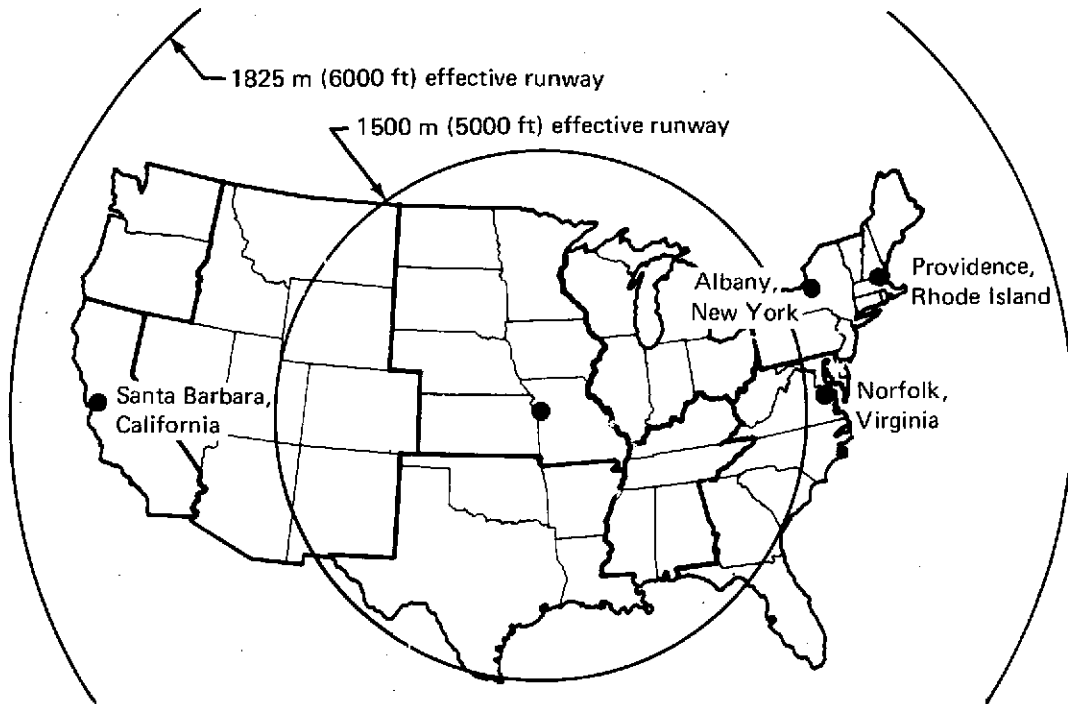
Two markets for a long-haul aircraft with reduced takeoff and landing characteristics have been investigated: (1) possible routes from cities with effective runways less than 2525 m (8300 ft); and (2) possible routes through suburban airports to alleviate congestion at neighboring principal airports.

Short Runway Cities. --The method of investigation was:

- a) Make a computer sort on all runways in the United States, identifying all runways, adjusted for altitude, that fell between 1500 m (5000 ft) and 2525 m (8300 ft) in length.
- b) This list was visually examined to eliminate airports where the area served included a second airport with longer runways available.
- c) The origin and destination traffic (1972) for each of the cities on the list was investigated for destinations in excess of maximum takeoff range for the standard TAC aircraft from these runways. Western cities were checked for major eastern destinations. Eastern cities were checked for major western destinations. There are few cities in mid-America that do not already have runways adequate for takeoff with destinations anywhere in the continental United States (see fig. 48a).
- d) The O and D traffic was projected into the 1980-2000 time period for the city pairs being investigated. Allowance was made for increased traffic resulting from non-stop service.
- e) Results: Four cities in the short-runway category were found that were projected to have the capability of supporting long-haul traffic on a limited service (one frequency a day or more) basis. These were:
 - 1) Norfolk, Virginia
 - 2) Albany, New York
 - 3) Providence, Rhode Island
 - 4) Santa Barbara, CaliforniaAll other cities either have adequate runways for conventional long-haul traffic or were judged to have too little traffic to support service in the 1980-2000 time period.

Suburban Airports. The suburban airport concept is designed so as to use satellite airports to relieve congestion at the major airport in the hub area. The basis for the concept is studies which show relatively small portions of the air traffic with original or final destination in the central cities involved. Figure 48b indicates 20% of 1967 air passengers originated and terminated in suburban areas. Projection of trends indicate that this fraction can be expected to increase to 33% by 1985.

a) ESTIMATED RANGE OF ATT AIRPLANE IF FUEL IS OFF-LOADED TO IMPROVE TAKEOFF FIELD LENGTH



b) INTERCITY AIR TRIP DISTRIBUTION TRENDS—1967-1985

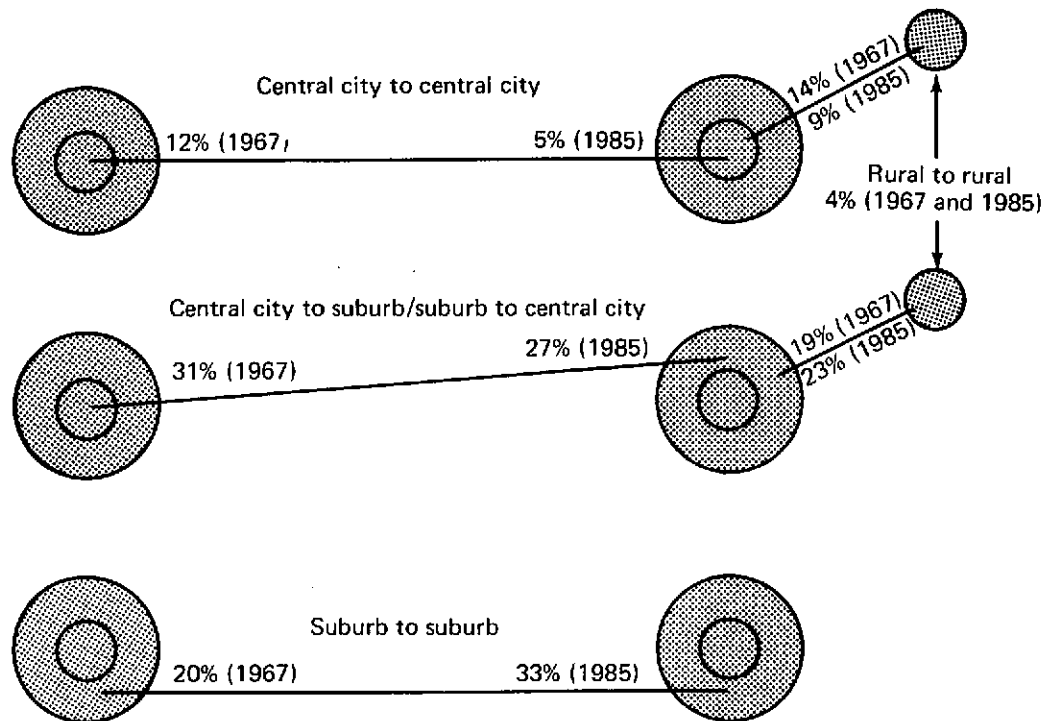


FIGURE 48.—MARKETING ASPECT FOR TAC-RTOL AIRPLANE

Many cities already have more than one airport with effective runway length greater than 2500 m (8000 ft). Los Angeles, San Francisco, Miami, Atlanta, New Orleans, Washington/Baltimore, New York, Denver, Dallas, and Seattle are among cities in this category. The above list, which is not all-inclusive, illustrates that many cities already have second airports, most in widely-separated locations relative to the city, which are capable of supporting conventional takeoff aircraft on long-range flights. In addition to these there are many smaller fields capable of taking short-haul traffic relieving the major hub for long haul.

In order to support a more-than-one airport concept a route must have sufficient traffic to support adequate service from each airport. Few long-range routes, even when the forecast growth into the '90s is taken into account, have adequate traffic density to support the concept. Many short-haul routes presently have this traffic density and more will have in the future. These routes are dense enough to permit fragmentation and still provide good competitive service. Suburban airports traffic is further fragmented by passenger destination preferences.

The secondary airport only serves its area. It will not adequately support flight changes because of the limited service possible in a fragmented market. Whenever flight changes are necessary, ground transportation between airports must be provided. This is expensive, inconvenient, slow, undependable in rush-hour traffic, and generally undesirable. Secondary airports should be limited to traffic to and from that city as initial originations or final destination. Few, if any, long-haul segments have adequate traffic to meet this criterion.

6.5 CONCLUSIONS

This task culminated with the configuration of four airplanes and the definition of these airplanes are the principal results. The major design conclusions are:

6.5.1 Congestion

- a) Airplane modifications can be accomplished, at cost in gross weight to achieve:
 - 1) High deceleration rates
 - 2) High-speed turnoffs
 - 3) Increased navigation/guidance/control accuracy (dependent on ATC capability)
- b) Significant improvements to runway operations are tied to tip vortex control techniques for which proven methods do not exist.

- c) Preliminary indications show potential passenger/pilot acceptance, separately, for each of:
 - 1) Steep descents
 - 2) Rapid decelerations
 - 3) High-speed takeoffsInsufficient data exist to confirm passenger acceptance of total scope of projected operational changes, however.
- d) Under the study assumptions, RTOL capability for long-haul aircraft would not provide significant opportunity for congestion relief.
- e) Capabilities for 5000-ft field length are most effectively achieved by conventional mechanical lift systems.

6.5.2 Noise

- a) Design trends suggest reduced dependence on flaps to achieve lift due to noise restrictions.
- b) Wing aspect ratio approaching 9.0 showed promise as a cost-effective means of improving both takeoff noise (three to five EPNdB) and approach speeds (15-kn increment).
- c) Improved aerodynamic L/D of advanced aircraft may work against steep approach capability—drag devices are required, particularly for adverse wind conditions that may be faced at airports with preferential runway direction noise restrictions.
- d) Secondary power-system reconfiguration can help provide noise improvements on approach for some aircraft icing weather conditions. Impact on APU size is large, incurring even more significant size requirements than required for powered wheels.

6.5.3 Emissions

- a) Advanced combustor design concepts rest largely on a model-scale data base. Design solutions for HC and CO tend to conflict with NO_x solutions.
- b) Advanced combustor technology projected by engine manufacturers does not alone satisfy study goals.
- c) Powered-wheel concept is one method offering potential to compensate for projected combustor technology deficiencies with respect to study HC/CO requirements.

- d) Powered-wheel design concept appears feasible but proof-of-concept development work is required.
- e) Revised engine cycle (lower OPR) offered potential to compensate for projected combustor technology deficiencies with respect to study NO_x requirements.
- f) Water injection as NO_x control was rejected because of previous logistics, maintenance, and engine life degradation histories with such systems.

6.5.4 General

- a) Noise and congestion design features should be consistent with essentially all-weather capability.
- b) No major design conflicts were encountered with respect to the various noise, congestion, and emission requirements.

7.0 TASK IV—TECHNICAL AND ECONOMIC ASSESSMENT

The objective of this task was to assess the costs and benefits associated with configuring the TAC and TAC-RTOL airplanes relative to the baseline ATT design. Results are given relative to a state-of-the-art airplane configuration in order to relate results to existing levels of technology. The assessment included an evaluation of the economic worth of delay reduction estimated to be achievable. The material is given in three parts:

Technical.—In section 7.1 a detailed technical comparison of the four airplanes central to the study is made in terms of principal airplane design parameters. A number of comparisons are made using takeoff gross weight and auxiliary airplane performance parameters such as field length capability, altitude capability, range factors, and others. In most cases, the design changes made result in reduced levels of airplane performance. However, this degradation in performance must be judged relative to the improvements added to promote increased airplane terminal-area compatibility. Therefore, a comparison is next given of the four airplanes in terms of the principal terminal-compatibility characteristics, namely, congestion, noise, and emissions. Finally, some brief miscellaneous trade studies of interest are documented. These trade studies largely deal with design decisions which were necessarily made in Task III somewhat arbitrarily. The intent of the trade studies was to review the impact of major design decisions which could equally well have been made in a different fashion.

Economic.—In section 7.2 a summary comparison of the four airplanes in terms of economic parameters is presented. Here the impact of the configuration changes made is viewed from a wider scope than just the airplane performance characteristics. This section includes as well such aspects as: acquisition costs associated with the design modification; additional maintenance burdens which may be imposed; and the overall assessment of operating costs and investment attractiveness in terms of net present value (NPV). In addition, in this section, a separate assessment is made of the individual terminal compatibility changes. The potential benefits which reduced aircraft delay might enable are given and trends shown as to how these cost savings may be offset against the design penalties incurred.

Cost/Benefit.—In section 7.3, the technical and economic assessments are combined to provide an overview of the costs in relation to the benefits provided.

7.1 TECHNICAL ASSESSMENT

7.1.1 Technical Comparison of Study Airplanes

Table 8 contains a comparison of the principal size, geometry, performance, and noise characteristics of the four study airplanes. The asterisks on the figure also give an indication of the sizing constraints which were critical in establishing engine, wing, and body sizes. As shown, all aircraft were designed for the same nominal 200-passenger/3000-nmi range. As noted previously in section 6.0, the principal design parameters that affect the airplane size are range and payload specification; takeoff field length and approach speed constraints; and initial cruise altitude capability.





The CWB airplane size was basically established by takeoff field length and selection of minimum airplane gross weight. Sufficient airplane capability existed for the remaining design sizing constraints. Similarly, the ATT airplane was thrust sized from takeoff field length considerations. Wing loading was established principally by selection of minimum takeoff gross weight.

In contrast, the TAC airplane wing was sized primarily from approach speed considerations. This speed is not an independent consideration from approach noise measured at the FAR Part 36 noise station. The situation arises because additional wing area can be traded against increased flap setting in order to achieve a desired noise level and still satisfy the approach speed constraint. The engine size for the TAC airplane was established not on the basis of takeoff field length but rather on the ability to achieve sufficient climb gradient to reduce the approach noise by some 5 EPNdB relative to the ATT airplane. This capability was primarily achieved by the use of the higher aspect ratio wing. Engine size was adjusted slightly from that required for minimum takeoff gross weight consistent with the desired climb gradient.

The TAC-RTOL airplane as already discussed had a wing sized by a combination of approach speed and approach noise qualities and its engine sized by a combination of field length restrictions and satisfactory climbout gradient associated with takeoff noise constraints.

Figure 49 presents a summary comparison of the principal performance parameters: range factor and OEW fraction. The trends shown are explainable in this way. Relative to the CWB airplane the ATT with its extensive use of advanced composite materials shows an appreciably improved OEW fraction. The range factor on the other hand shows considerable degradation. This is due to a combination of reduced cruise L/D (due in part to use of a moderately thick supercritical wing) and propulsion installation inefficiency incurred because of the extensive use of acoustic treatment. Relative to the ATT airplane the TAC and TAC-RTOL airplanes incur penalty in OEW due to the many features added to provide terminal compatibility. Of these features, the changes to improve low speed aerodynamics also provided improvements to cruise range factor. These stem primarily

TABLE 8.—SUMMARY AIRCRAFT CHARACTERISTICS^a

Characteristic				
	CWB	ATT	TAC	TAC-RTOL
Cruise speed, mach	0.85	0.90	0.90	0.90
Takeoff gross weight, kg (lb)	152 400 (336,000)	137 100 (302 200)	141 100 (311 100)	149 700 (330 000)
Operating weight empty, kg (lb)	88 000 (194,000)	72 200 (159 200)	78 300 (172 630)	84 000 (185 290)
W/S, N/m ² (lb/ft ²)	5190 (108.4)	6290 (131.3)	5800 (121.2)	5800 (121.1)
T/W	0.297	0.308	0.299	0.343
Thrust/engine, sea level static, N (lb)	148 100 (33 300)	138 300 (31 100)	103 200 (23 200)	125 900 (28 300)
Number of engines/type	3/CF6-6D	3/ATSA 4-2800-24	4/ATSA 4-2800-24	4/ATSA 4-2800-24
Acoustic	Periphery	2 rings/1 splitter	2 rings/1 splitter	2 rings/1 splitter
Wing area, m ² (ft ²)	288 (3100)	214 (2300)	239 (2570)	253 (2720)
Sweep, rad (deg)	0.611 (35.0)	0.637 (36.5)	0.637 (36.5)	0.637 (36.5)
Aspect ratio	6.8	7.6	9.0	9.0
Performance				
Takeoff field length (304.8m/32.2°C), m (1000 ft/90°F), ft	2530 (8300)	2530 (8300)	2530 (8300)	1520 (5000)
Initial cruise altitude capability, m (ft)	10 700 (35 100)	11 000 (36 200)	11 800 (38 800)	12 300 (40 400)
Approach speed, m/s (kn)	62.8 (122)	69.5 (135.0)	61.8 (120.0)	61.8 (120.0)
Range factor, km (nmi)	1 990 (10 740)	1810 (9790)	2 010 (10 860)	2010 (10 860)
Community noise (est/est—FAR part 36) using FAR abatement procedures:				
Takeoff noise with cutback power	96.7/-7.1	95.7/-7.3	88.2/-15.0	88.7/-14.9
Sideline noise	95.6/-10.7	93.6/-12.4	90.3/-15.8	91.2/-15.1
Approach noise	104.7/-1.6	98.5/-7.5	97.9/-8.2	98.0/-8.3
Traded noise, ΔEPNdB	-3.6	-9.0	-10.2	-10.3

^a5560 km (3000 nmi) range; 18 140 kg (40 000 lb) payload

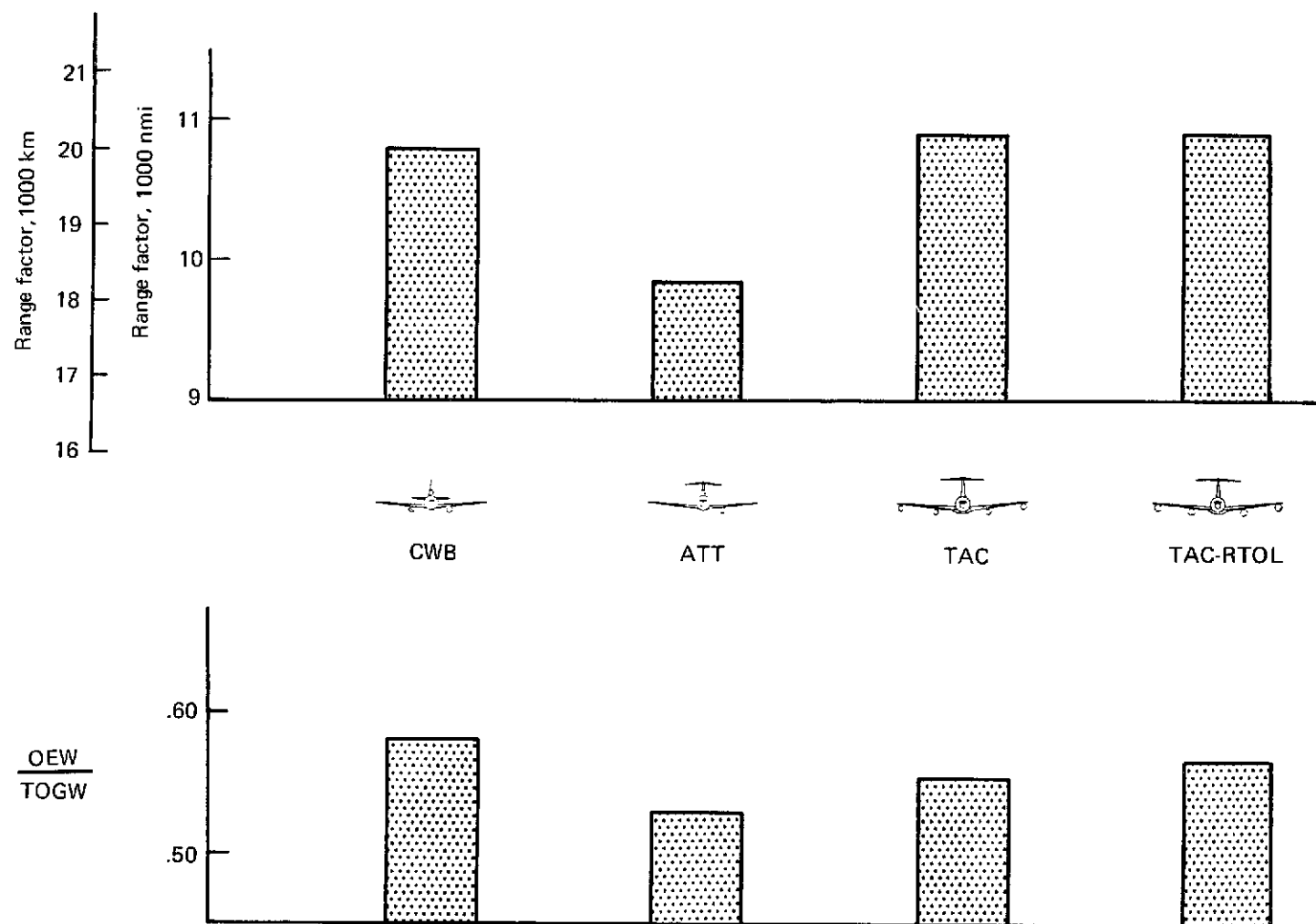


FIGURE 49.—SUMMARY PERFORMANCE CHARACTERISTICS OF STUDY AIRPLANES

from the increased aspect ratio and increased wing area both of which tend to improve cruise L/D. Range factor of the TAC-RTOL airplane is essentially unchanged from that of the TAC airplane. However, the OEW fraction has been penalized somewhat for the larger engine size.

Figure 50 presents a slightly more detailed comparison showing approach speed, cruise Mach number and a breakdown of range factor into its aerodynamic and propulsive efficiency factors. One additional fact which might be noted in this figure is a slight improvement in propulsive efficiency between the baseline ATT and TAC airplanes. This improvement in efficiency is a result of: (1) changing the engine configuration from one which includes S-duct internal losses to the four-engine on-the-wing configurations used for the terminal area compatible airplanes, and (2) an improvement realized in the cruise SFC for the primary engines as a result of utilizing an in-flight dedicated auxiliary power unit for the TAC airplanes. The savings result from penalties associated with bleed and horsepower extraction which were incurred by fuel expended by the APU units. In actual calculations it was shown that the fuel expended by the APU unit in fact is about equivalent to that saved by the main engines.

Table 9 presents a detailed breakdown of the principal weight categories for the four study airplanes. Reduced wing weight of the ATT airplane relative to the CWB airplane is a result of the use of a relatively thick NASA supercritical wing in conjunction with extensive use of advanced composite structures. A significant increase in wing weight is encountered in going to the TAC configuration both as a result of the increased wing area and the higher aspect ratio. Of the OEW increment shown, about 70% is accounted for by the change in aspect ratio. A large part of the remaining 30% is due to the change in wing area and some smaller portion is associated with secondary effects on such items as the airplane vertical fin.

Increased weight of the vertical tail between the TAC and the ATT aircraft and again between the TAC-RTOL and the TAC airplane is due largely to the increased tail area associated with the control requirement for engine-out conditions occasioned by the more outboard spanwise location of the propulsion system and by the larger thrust size of that engine respectively.

Differences in body weight between the ATT and CWB airplanes reflect the advanced technology application of the composite structures and the reduced fuselage wetted area and diameter of the ATT airplane. In addition, the ATT airplane is credited with weight savings as a result of the lower gross weight of the entire airplane. The small increase in body weight for the TAC airplane relative to the ATT airplane is also associated partly with increased body wetted area and the slightly higher gross weight of the TAC airplane. The change between the TAC-RTOL weight and the TAC weight for the body/nacelle/strut group is due largely to the changes in engine nacelle and thrust size required for the higher thrust loading of the RTOL airplane. Relative to the ATT airplane, the landing gear of the TAC airplane increases to account for (1) increased brake weight, and (2) as a

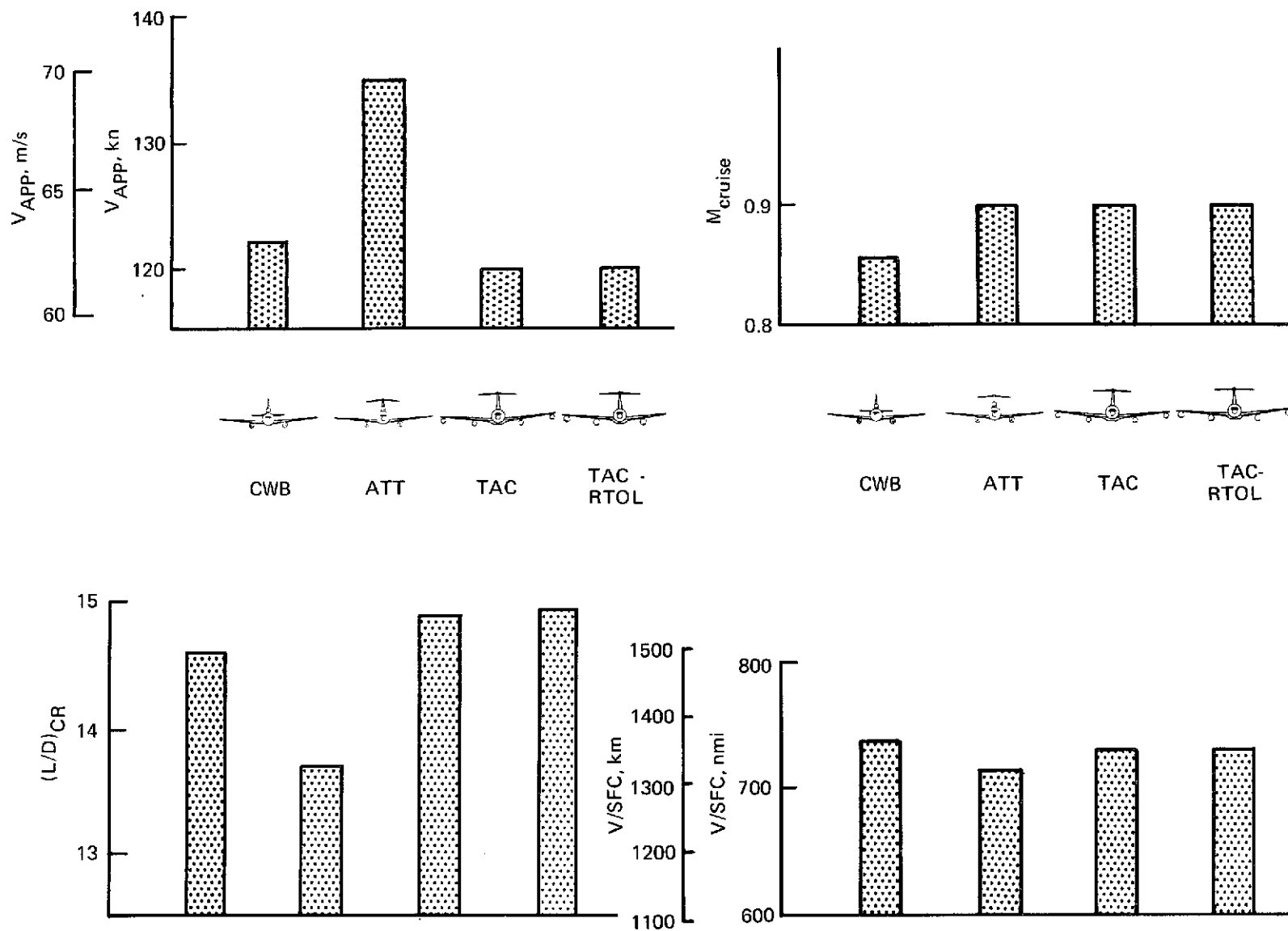






FIGURE 50.—ADDITIONAL PERFORMANCE CHARACTERISTICS COMPARISON

TABLE 9.—COMPARATIVE WEIGHTS BREAKDOWN

Item	 ATT kg (lb)	 CWB kg (lb)	 TAC kg (lb)	 TAC-RTOL kg (lb)
Wing group	13 136 (28 960)	14 352 (31 640)	16 788 (36 990)	18 434 (40 640)
Vertical tail	1184 (2 610)	1347 (2 970)	1442 (3 180)	2245 (4 950)
Horizontal tail	1483 (3 270)	2758 (6 080)	1256 (2 770)	1343 (2 960)
Body group /nacelle & strut	17 767 (39 170)	2 1673 (47 780)	18 683 (41 190)	19 827 (43 710)
Landing gear	5361 (11 820)	7747 (17 080)	6033 (13 300)	6273 (13 830)
Propulsion group	10 210 (22 510)	9952 (21 940)	9417 (20 760)	11 231 (24 760)
Fixed equipment	17 264 (38 060)	18 098 (39 900)	18 665 (41 150)	18 665 (41 150)
Standard & operational items	5094 (11 230)	5484 (12 090)	5157 (11 370)	5 157 (11 370)
Miscellaneous	871 (1 920)	1021 (2 250)	871 (1 920)	871 (1 920)
OEW	72 370 (159 550)	82 432 (181 730)	78 302 (172 630)	84 046 (185 290)

result of housing the powered wheel assembly an additional penalty is levied because of the increased unsprung mass supported by the landing gear. No essential differences are seen in terms of propulsion group weight except that the TAC-RTOL airplane incurs an 1820 kg (4000 lb) OEW penalty because of the larger engine size. Fixed equipment weight increment for the TAC airplanes reflects the increased APU size and number. Little change exists between the remaining weight group items. A summary OEW statement is provided in the figure.

Figure 51 summarizes the basic thrust loading and wing loading characteristics for the four study airplanes. The reasons for the data trends have been discussed previously.

Figure 52 illustrates the breakdown of the weight penalties added to provide the separate terminal compatibility design features. The figure also shows the incremental effect for each of the items on airplane TOGW. The split between the penalties incurred in structural efficiency and the penalties incurred in range factor (for aerodynamic and propulsive efficiency) is presented. The basic reasons for the various penalties have already been given in section 6.3 where the principal terminal compatibility design changes were extensively discussed.

7.1.2 Assessment of Terminal Compatibility Benefits

The total scope of the terminal area compatibility study has been three-pronged in terms of defining causes and potential remedies for airplane congestion, noise, and pollution impact.

The effect of various changes to an advanced airplane and the resultant effect on several airports out to the year 2000 has been presented in section 5.0. In section 6.0, design decisions were made for a number of modifications to a baseline airplane to provide both a terminal-area-compatible airplane and a second terminal-compatible airplane with RTOL capability. Results presented so far in section 7.0 showed the performance impact on the four study airplanes. The impact of the modifications to the TAC and TAC-RTOL airplanes generally degraded their efficiency. This section separately summarizes the congestion, noise, and emissions improvements which these modifications have brought about.

7.1.2.1 Congestion

Figure 53 shows a summary in terms of delay due to congestion, projected into the future. The curve is a repeat of one presented earlier but the chart now reflects the capabilities of the TAC and TAC-RTOL airplanes. The curve illustrates the potential for achieving the 6-min busy hour delay criteria that a fleet of terminal-compatible aircraft operating into the 1990-2000 time period possess. Moreover, achievement of this goal should be viewed in terms of the potential alternative. That alternative, for LAX airport at least, would be tantamount to allowing intolerable levels of

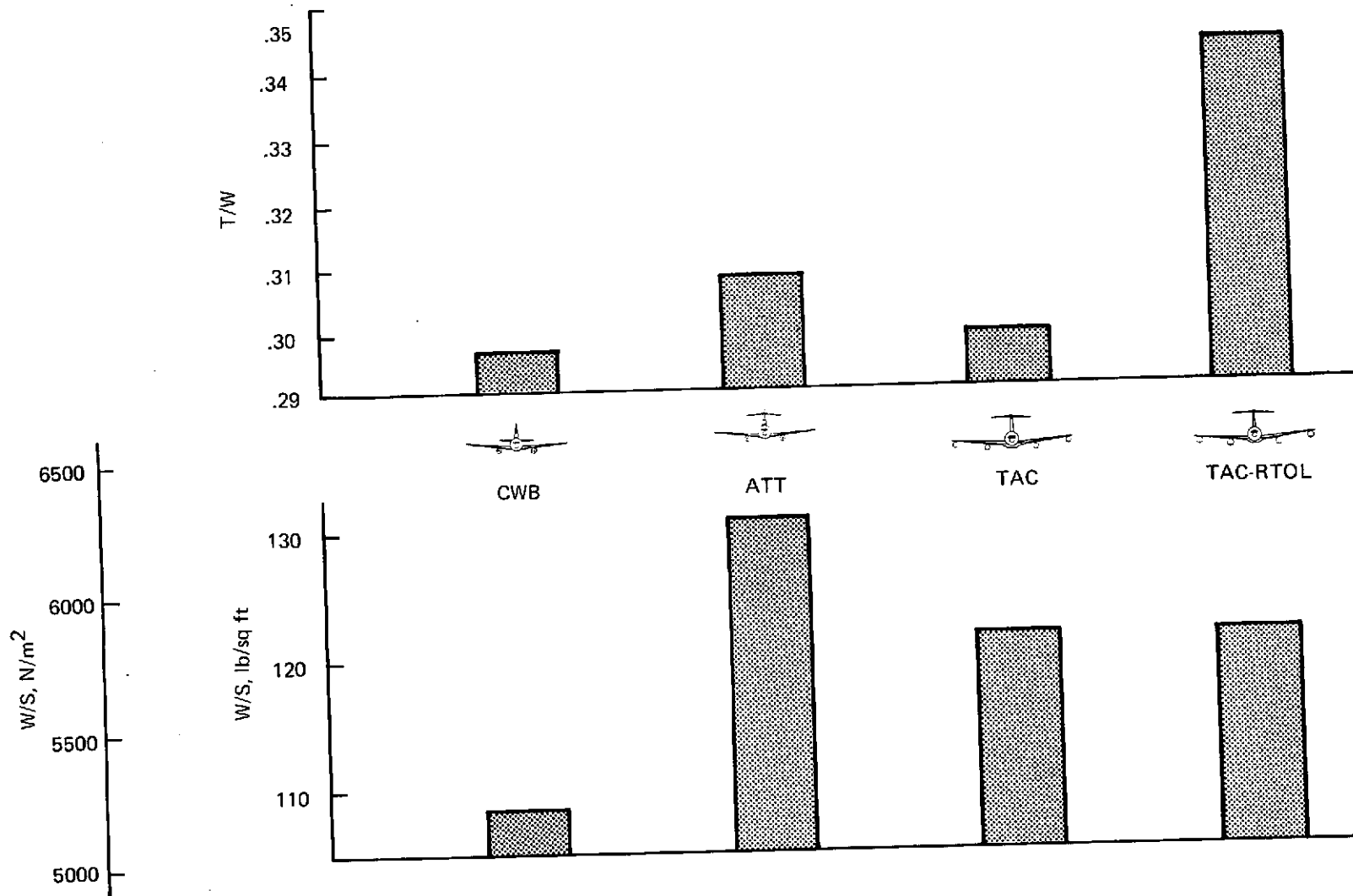
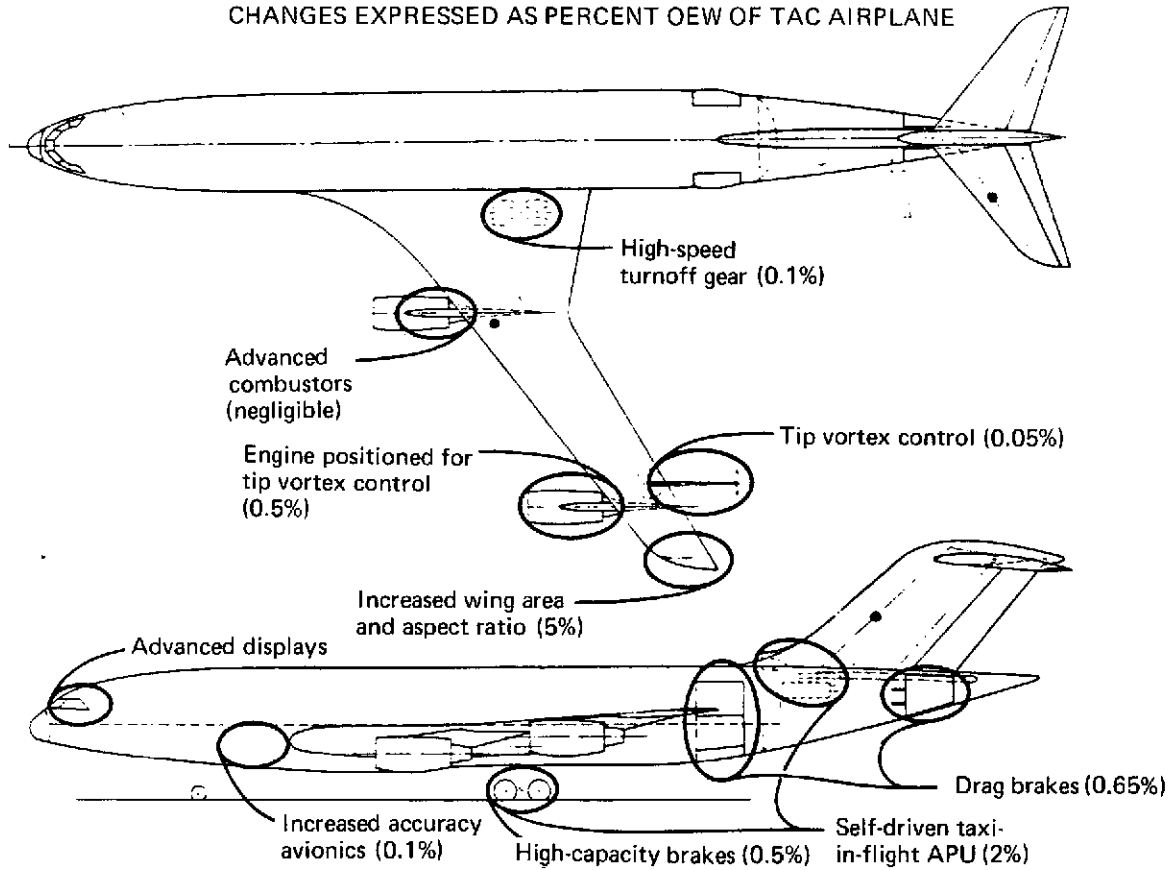


FIGURE 51.—ENGINE AND WING SIZE COMPARISON—AIRPLANE CHARACTERISTICS SUMMARY

ESTIMATED WEIGHT PENALTIES FOR TERMINAL-COMPATIBLE DESIGN
CHANGES EXPRESSED AS PERCENT OEW OF TAC AIRPLANE



INCREMENTAL TOGW PENALTIES FOR TERMINAL-COMPATIBLE DESIGN MODIFICATIONS

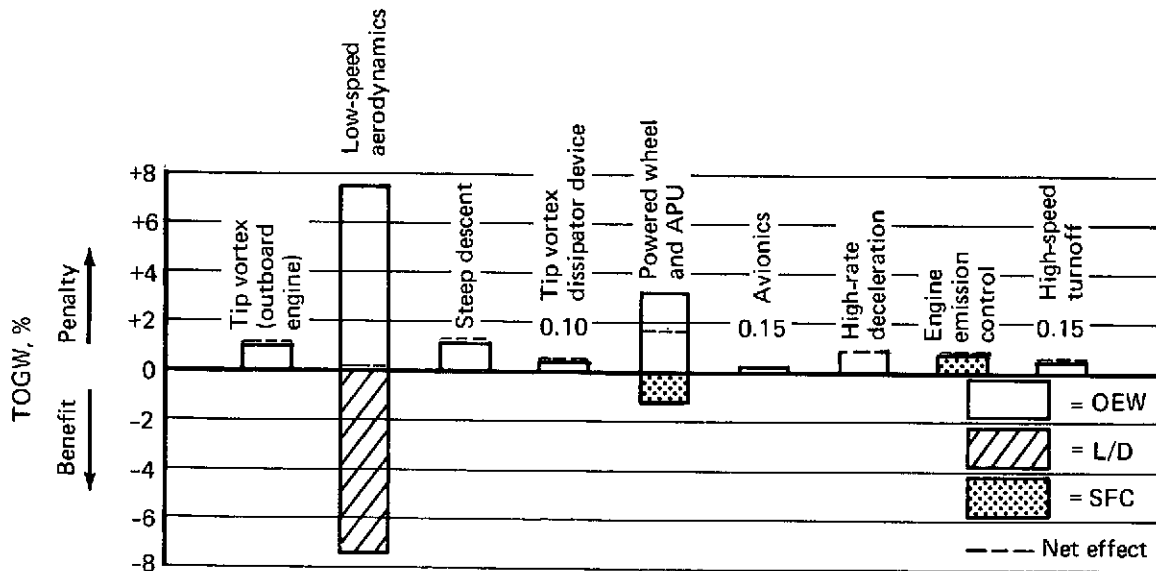


FIGURE 52.—PERFORMANCE IMPACT OF TERMINAL-COMPATIBILITY DESIGN

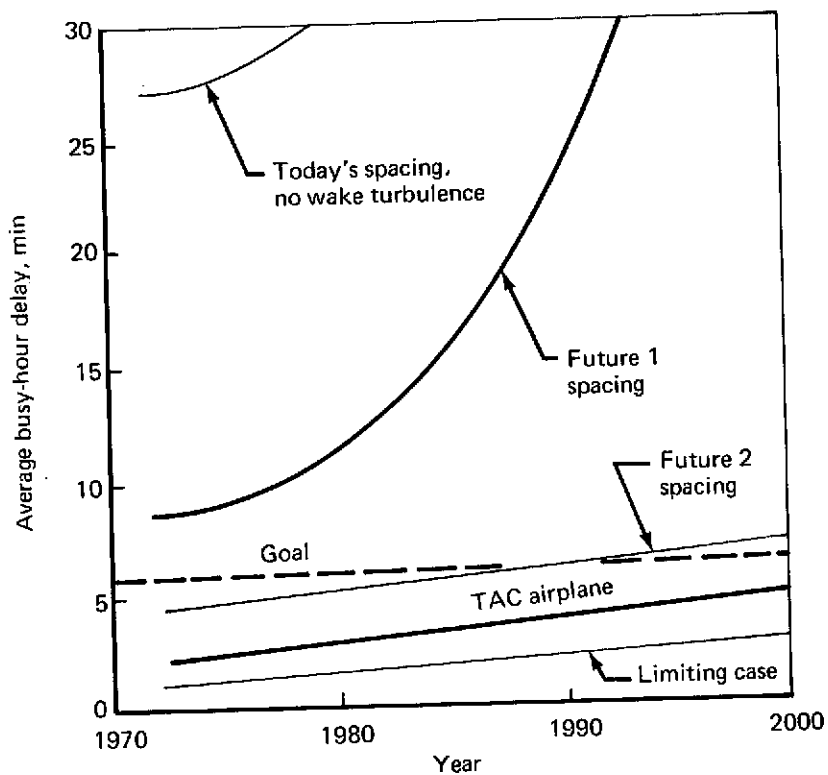
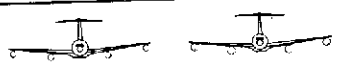
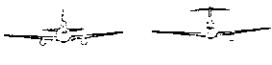


FIGURE 53.—TERMINAL-COMPATIBILITY BENEFITS—BUSY-HOUR DELAY(LAX)

TABLE 10.— TERMINAL AREA COMPATIBILITY BENEFITS—
AIRPORT DELAY COMPARISON

Year	Delay, min					
	 TAC & TAC-RTOL			 CWB & ATT		
	Daily average			Busy-hour average		
	LAX	JFK	ORD	LAX	JFK	ORD
1980	1.2	4.1	32	2.7	10.8	90
1990	1.6	9.3	*	3.7	25	*
2000	1.7	41	*	4.0	105	*

* Airport saturated—unable to handle demand—
delays very large

delay. This last statement is valid even if some design improvements, of less dramatic scope than applied to the TAC airplane are made.

Table 10 illustrates the same point in slightly broader perspective showing daily-hour and busy-hour average delay levels for the three airports assessed in the current study. For simplification, the CWB and ATT airplanes have been grouped together and represent an equivalent capability in terms of reduced congestion, as have the TAC and TAC-RTOL airplanes. This figure reflects the fact that without terminal compatibility improvements, all of the study airports, even as early as the year 1980, would suffer severe congestion. As shown previously, the TAC airplane would be able to achieve tolerable levels of delay when confronted with the projected demand into LAX airport. However, as shown in the table, the projected demand for both JFK and ORD would by 2000, even in the case of the TAC capability, again lead to saturated airport conditions and inability to handle the traffic demand. The implication, of course, is that changes beyond those incorporated into the TAC airplane would be required to provide for orderly conditions at the two latter airports.

7.1.2.2 Noise

An assessment of the comparative noise impact between the four study airplanes is presented in terms of two noise impact parameters. First, a comparison is made on the basis of the three FAR Part 36 measurement stations. In accordance with current practice, a traded noise level is presented which averages evaluation of the three (takeoff, sideline, and approach) criteria. In addition, comparison is made in terms of the community impact as assessed by area contained within the 90-EPNdB noise contour. This latter assessment is particularly useful in assessing approach noise since many of the noise abatement approach procedures are not credited for noise reduction under the current FAR Part 36 assessment. This results because of (1) the single location of the approach noise measuring point and, (2) its relationship to the geometry of a two-segment approach with lower-segment capture altitude of 500 ft or greater.

Figure 54 shows a comparison between the CWB, the ATT, the TAC, and the TAC-RTOL airplanes. Takeoff, sideline, approach, and traded noise levels are all shown for conditions which both include and exclude estimation of airframe noise. It should be recalled that in spite of the two-segment approach path of the TAC airplanes, the geometry is such that on approach all airplanes are assessed on a final three-degree approach glidescope.

As shown on the plot, sideline noise for all aircraft is in the neighborhood of about 10 to 15 EPNdB below FAR Part 36. Both of the TAC airplanes are 2 to 4 EPNdB below the others.

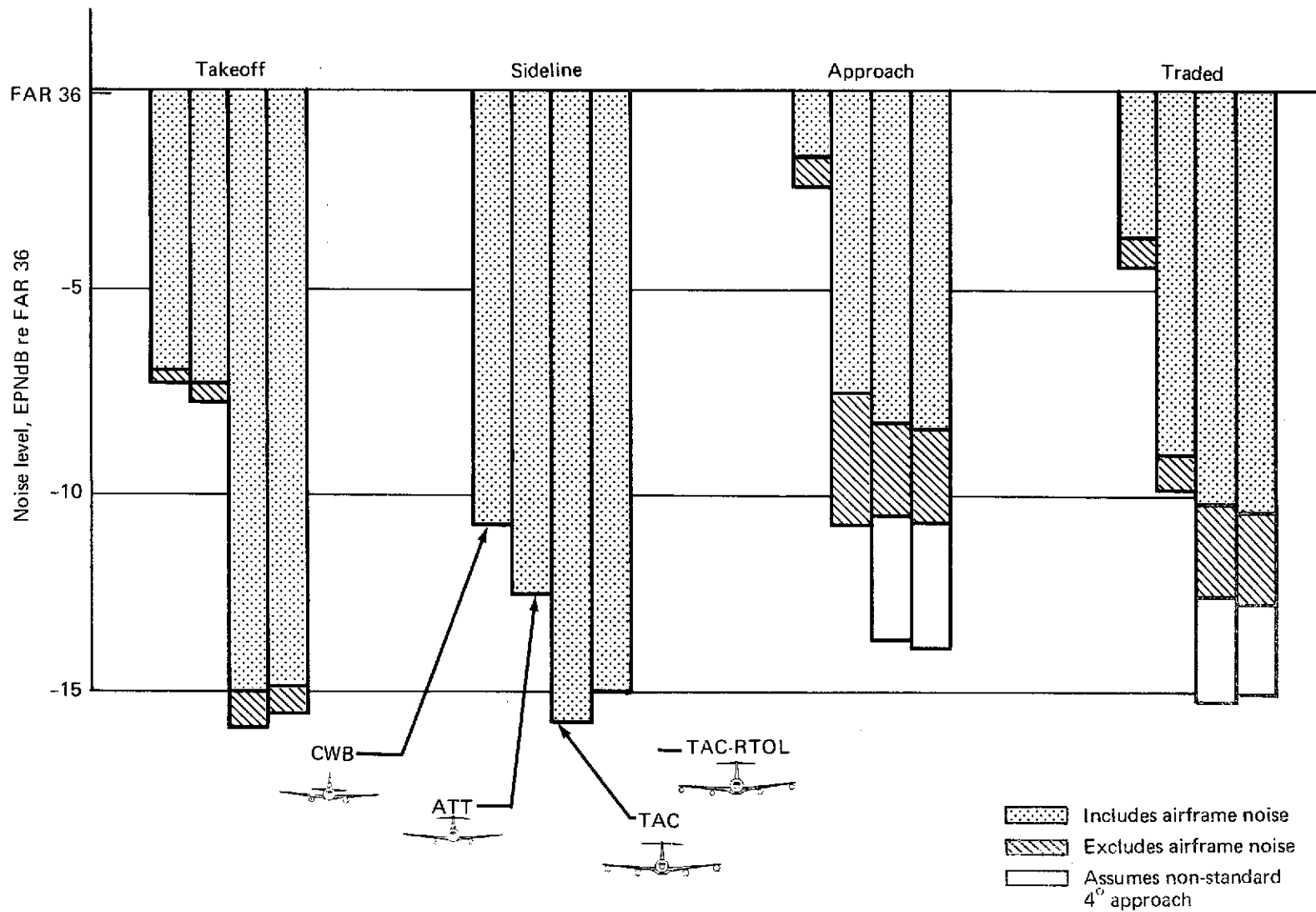


FIGURE 54.—TERMINAL COMPATIBILITY BENEFITS—FAR PART 36 NOISE COMPARISON

For takeoff noise we see that CWB and ATT noise levels are of the same magnitude. This is the result of a quieter engine for the ATT but a shallower climb-out gradient. Both the TAC and the TAC-RTOL airplanes, by design, have takeoff noise levels showing improvement on the order of 7 to 8 EPNdB.

The approach noise levels show an advantage of 5 to 7 EPNdB for the ATT airplane relative to the CWB. This advantage is not based on a completely comparable set of circumstances, however, since the CWB airplane is configured to a somewhat lower approach speed than the ATT airplane. The approach noise of the TAC airplanes relative to the ATT airplane is explained by a combination of factors; first, the improved low-speed aerodynamics allows improved lift/drag for which reduced airplane thrust levels can be achieved on a given glideslope. Thus the TAC airplanes are operating at relatively lower throttle settings than the ATT. However, the lower thrust setting advantages of the TAC airplanes is offset by the fact that the assumed vortex-dissipating blockage device is incurring additional airplane drag. This requires that the airplane thrust level be increased accordingly. The net result is a comparable approach noise level for both airplanes.

The traded noise levels show much the same trends as the approach noise levels since the TAC airplanes are essentially dominated by their approach noise.

A contributing factor to the relatively high approach noise levels of all the airplanes is the problem of airframe (i.e., nonpropulsive) noise. The data shows that when this airframe noise is included, the TAC approach noise level is limited to the order of eight EPNdB below FAR Part 36. This results in a traded noise level on the order of 10 EPNdB below FAR Part 36. Stated in these terms, the traded noise level does not seem to reflect fair credit upon the -15 EPNdB noise levels of these airplanes on takeoff and at sideline, however.

Let us assume that since airframe noise is only first beginning to be understood, then additional research and development funding could somewhat improve the situation. If gains are made so that airframe noise does not contribute to the overall airplane approach noise, then as shown in figure 54, the TAC airplanes would achieve a noise level of about -10 EPNdB relative to FAR Part 36 on approach (see fig.). This would result in traded noise levels on the order of 12 EPNdB below FAR Part 36.

A final additional observation to be made is this: if, as a result of community noise impact, it is shown to be desirable that approach noise be further reduced, consideration can be given to the TAC airplane adopting a 4 degree final approach glide slope. This would have the effect of reducing approach noise levels to the order of 13 EPNdB below FAR Part 36, so that with traded noise a balanced noise level of about -15 EPNdB would be achieved for all three FAR Part 36 stations.

The question can be asked—if the TAC airplanes are credited with noise levels associated with a four-degree final approach why would not the ATT and CWB airplanes be given like credit? a partial answer is this—“many of today’s existing aircraft are unable to operate on steeper approach paths than three degrees in conditions of tail wind and wind shear. The difficulty is that under conditions of excessive tail wind such aircraft do not have sufficient ability to deploy drag with the result that the tail wind tends to blow them off course and prevents them from maintaining the desired steep glide slope. The TAC airplanes, on the other hand have been configured, and provided with such a drag capability by means of the aft-fuselage speed brakes and could handle a four-degree final approach glideslope in nearly all wind conditions. Under these circumstances it may not be unreasonable to consider that, in fact, the TAC airplanes can potentially achieve a -15 EPNdb traded noise level as a result of the terminal compatibility design features which have been incorporated relative to the baseline ATT airplane.”

Figure 55 shows a comparison in terms of 90 EPNdB noise footprints for the four study airplanes. The relative area is shown utilizing the CWB area as a base. Again, for this plot, *airframe noise has not been included*. The total footprint areas are shown apportioned between the takeoff and approach contributions. As the reader will notice, relative to the CWB airplane, the ATT airplane provides a footprint area reduction on the order of 33%. Relative to the same CWB baseline the TAC airplane shows noise improvement on the order of 46%. The TAC-RTOL airplane shows an area reduction similar to the TAC airplane.

The TAC noise contour area relative to the ATT however is only reduced a small amount, even though the TAC uses a nine-degree/three-degree approach and the ATT used the normal three-degree approach. Two major reasons account for this small difference in areas. First, figure 55 shows that approach area constitutes only a small percentage of the total 90-EPNdB area. Second, figure 56 shows that a heavily-treated (2R/1S) ATT engine during a three-degree approach produces about the same 90-EPNdB area as a heavily-treated (2R/1S) TAC engine during a nine-degree/three-degree approach. Basically, the reduced source noise levels are already approaching 90-EPNdB and thus path variations have no effect.

The nine-degree/three-degree two-segment approach would however be highly effective in reducing 90-EPNdB approach area for peripherally-treated engines. For example, if the ATT and TAC airplanes are compared on the basis of peripherally-treated engines the noise abatement nine-degree/three-degree two-segment approach would show considerable improvement relative to a conventional three-degree glideslope. Figure 56 shows this to be on the order of an 80% reduction in approach area.

During takeoff a peripherally-treated ATT (or TAC) engine would provide almost the same 90-EPNdB takeoff noise contour as the heavily-treated (2R/1S) ATT (or TAC) engine. This is explained by the fact that for takeoff, at altitudes about 910 m (3000 ft) say, the high-frequency

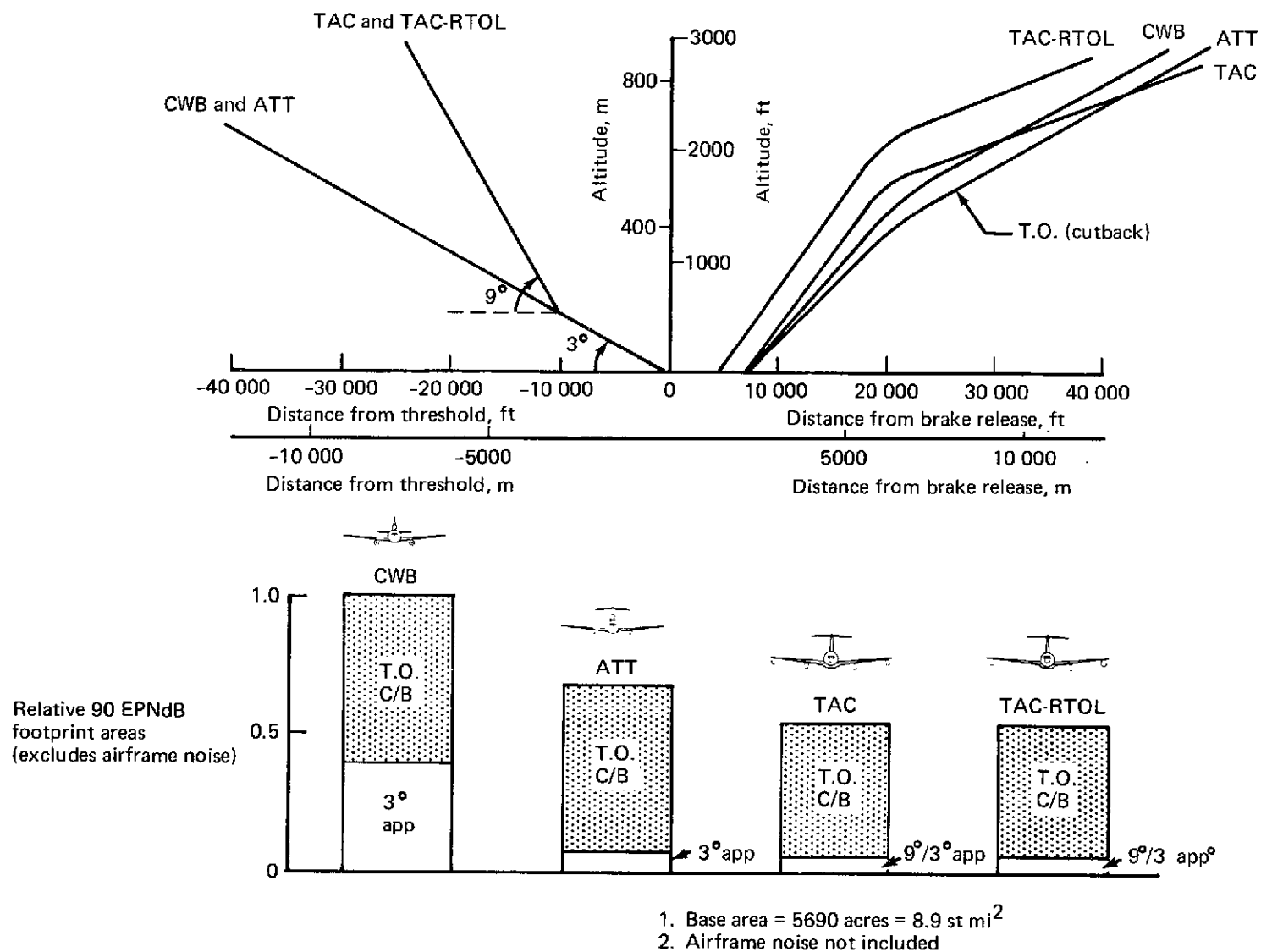


FIGURE 55.—TERMINAL-COMPATIBILITY BENEFITS—NOISE FOOTPRINT AREA COMPARISON

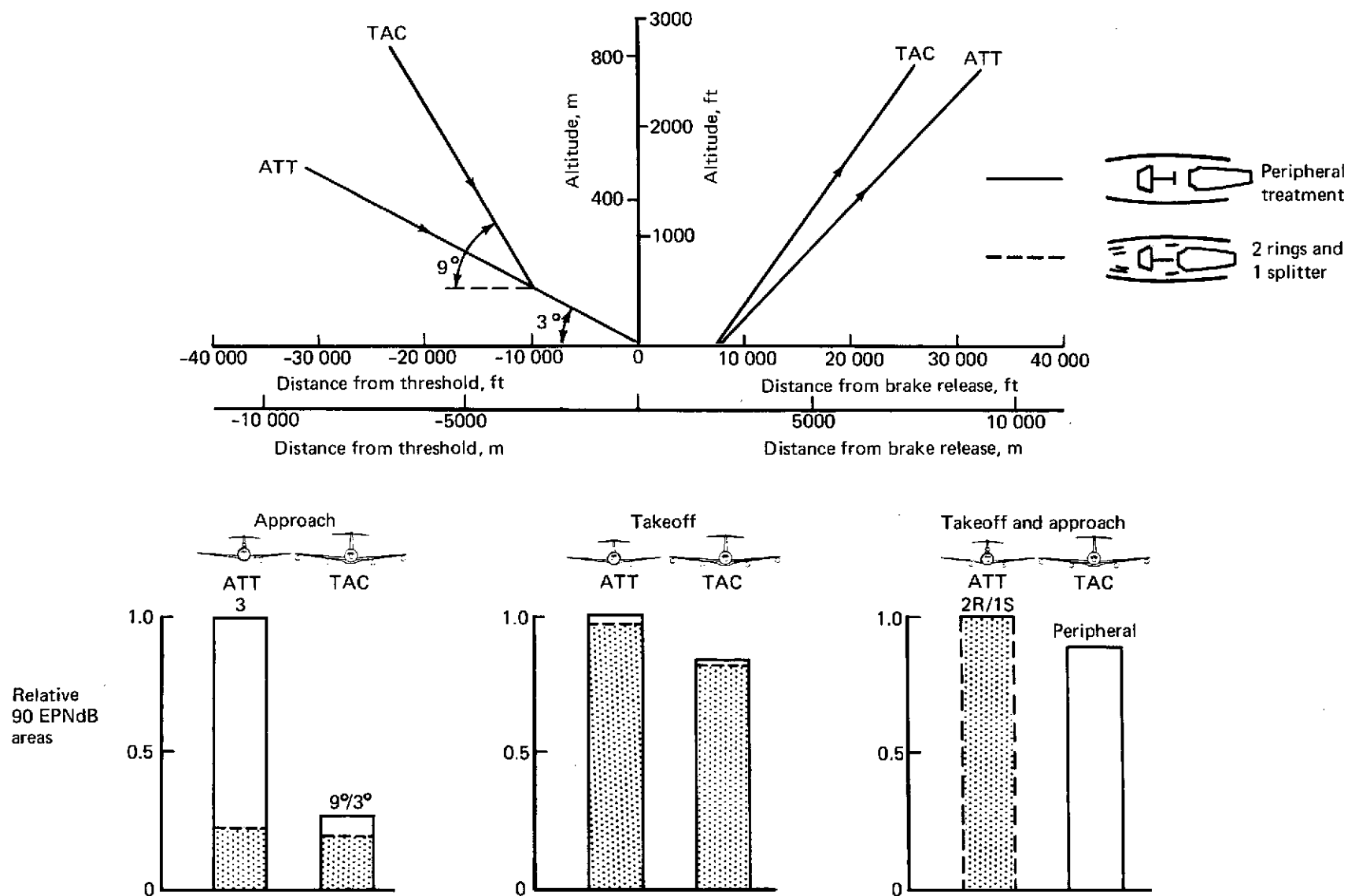


FIGURE 56.—TERMINAL-COMPATIBILITY BENEFITS—RELATIVE IMPACT OF TREATMENT VS FLIGHTPATH

engine noise components—those reduced by noise treatment—are attenuated substantially below the low frequency noise by atmospheric absorption.

The result of this TAC and ATT comparison is to show the attractiveness of peripherally-treated engines for the TAC and ATT in conjunction with noise abatement two-segment approaches.

7.1.2.3 Emissions

A summary of the emission impact is contained in figure 57. This shows for the four airplanes of interest the total pollutant emissions for a given landing takeoff cycle in terms of pounds of pollutant for CO, HC, and NO_x. The data are shown for two specific estimates of the time involved in the landing takeoff cycle and are labeled according to whether the EPA cycle time or a Contractor-developed minimum-delay cycle time is used.

Considerable differences exist with respect to the various airplanes shown. Specifically, the CWB airplane is configured with a main engine combustor representative of current technology; an APU sized essentially for ground operation; and is assumed to be operated on the ground using main engine thrust for taxiing. The ATT airplane is outfitted with an advanced combustor but still utilizes main-engine thrust for ground operations and incorporates an APU sized for ground operations. The TAC airplanes are also configured with an advanced technology combustor comparable to that on the ATT airplane. However, they do utilize the powered-wheel system for the primary portion of ground operating time. They also utilize two large APUs which have been sized for cruise and consequently are running at a less efficient part-throttle setting for ground operations.

The figure shows, that with respect to carbon monoxide, the ATT airplane accumulates about 60% of the total pollutant emission of the CWB airplane. The TAC airplanes, in turn, emit on the order of only half of that of the ATT airplane. It is interesting to note that whereas for both the ATT and CWB airplanes the bulk of the CO pollutant is attributable to the main engines, in case of the TAC airplane (as might be expected) the bulk of the pollutant is attributable to the auxiliary power units.

Similar trends are shown with respect to hydrocarbons, although in this case existing data suggested that APU technology would be such that hydrocarbon contributions would be negligible even for the TAC airplane. Comparison of the NO_x pollutants shows considerable improvement between the CWB airplane and the ATT airplane. This is associated with the improved combustor technology. A small part of the improvement of the TAC airplanes relative to the ATT airplanes is a result of a slight additional change made to the engine cycle in order to achieve the NO_x goals for the current statement of work. The reader will also notice that whereas the minimum delay landing takeoff times, show about a 40% CO and HC improvement relative to the EPA cycle times such

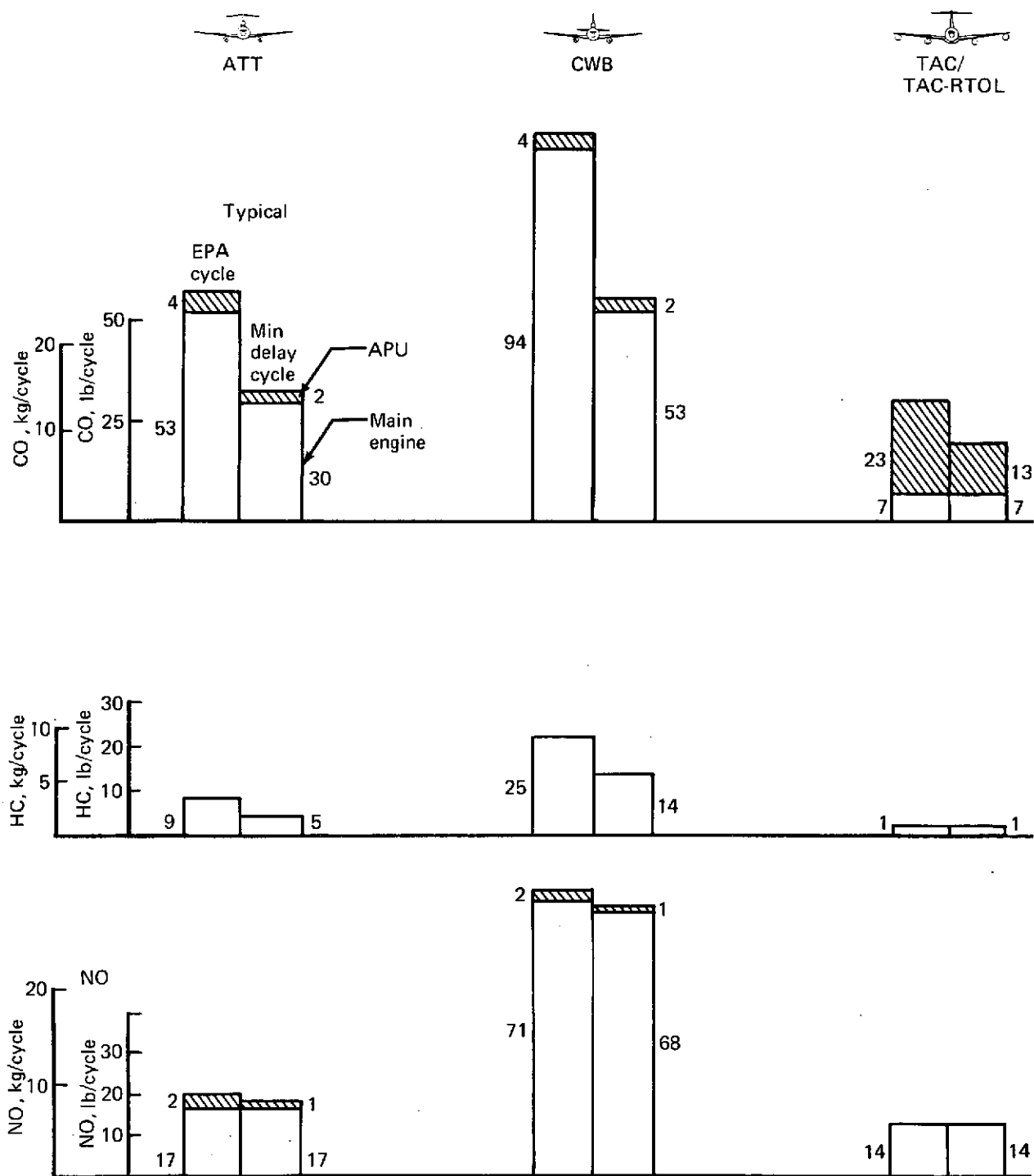


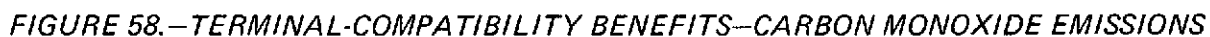
FIGURE 57.—TERMINAL-COMPATIBILITY BENEFITS—EMISSIONS PER LANDING/TAKEOFF CYCLE

improvement is not evident for the NO_x emissions. This is because the difference in cycle times is largely associated with ground operations for which the contribution from NO_x is negligible, the NO_x pollutants being discharged largely at the high power setting associated with takeoff and approach.

Figures 58, 59, and 60 illustrate in slightly more detail the interplay, for each of the pollutants considered, between the various approaches to reduce the total number of pounds per cycle. These approaches include combustor improvement, improvements to ground congestion, use of a powered wheel and moderate change in engine cycle. As shown in figure 58 for carbon monoxide, the various control approaches just mentioned are completely independent and at least four different options can be used to achieve a given level of pollutant per landing-takeoff cycle.

Another point can be made with the help of this figure. Variations in engine emission index are shown beginning with combustor technology as it stands today; proceeding to levels projected for an advanced combustor; and finally to the limits specified by the current contract goal. As an airframe manufacturer, the contractor judged that projections for combustor technology advancement are best made by the engine manufacturers. Therefore to overcome the shortfall between the contract statement of work goal and the combustor projections it was decided to interpret the contract goal in terms of an equivalent reduction in the total lbs of pollutant per cycle. The figure shows, for example, that for conventional ground taxi, using the EPA cycle times and using the engine manufacturer's projection of 35 lb of carbon monoxide per 1000 lb of fuel a total of 60 lb pollutant would be emitted for each LTO cycle. The contract statement of work specifies a combustor technology on the order of 20 lb of carbon monoxide per 1000 lb of fuel. This would result in approximately 33 lb of pollutant per LTO cycle. For the purposes of this study, the 20 lb/1000 lb of fuel goal was interpreted in terms of its equivalent, namely 33 lb of pollutant per landing takeoff cycle. In this case, even if combustor technology is assumed only to achieve pollution reduction on the order of 35 lb per 1000 lb of fuel, the contract goal can still be achieved provided, as shown in the figure, an overall reduction in ground congestion is made such that landing-takeoff-cycle times are more accurately reflected by the minimum-delay cycle than by the EPA cycle. In this case, reduction of congestion would have enabled achievement of the carbon monoxide aircraft emission goal.

Similarly, other projections can be shown whereby, if the airplane is equipped with powered wheel system and the EPA cycle is assumed to be representative of operating times then again, with the less optimistic engine combustor technology, the overall aircraft emission goal can be achieved when interpreted in terms of total lbs of pollutant per cycle. Option 1 shown on the figure of course, would represent utilizing the powered wheel system and also achieving the delay reduction. A point is shown also, which combines the combustor technology level of 20 lb per 1000 lb of fuel plus the powered wheel, plus the improvements to delays.



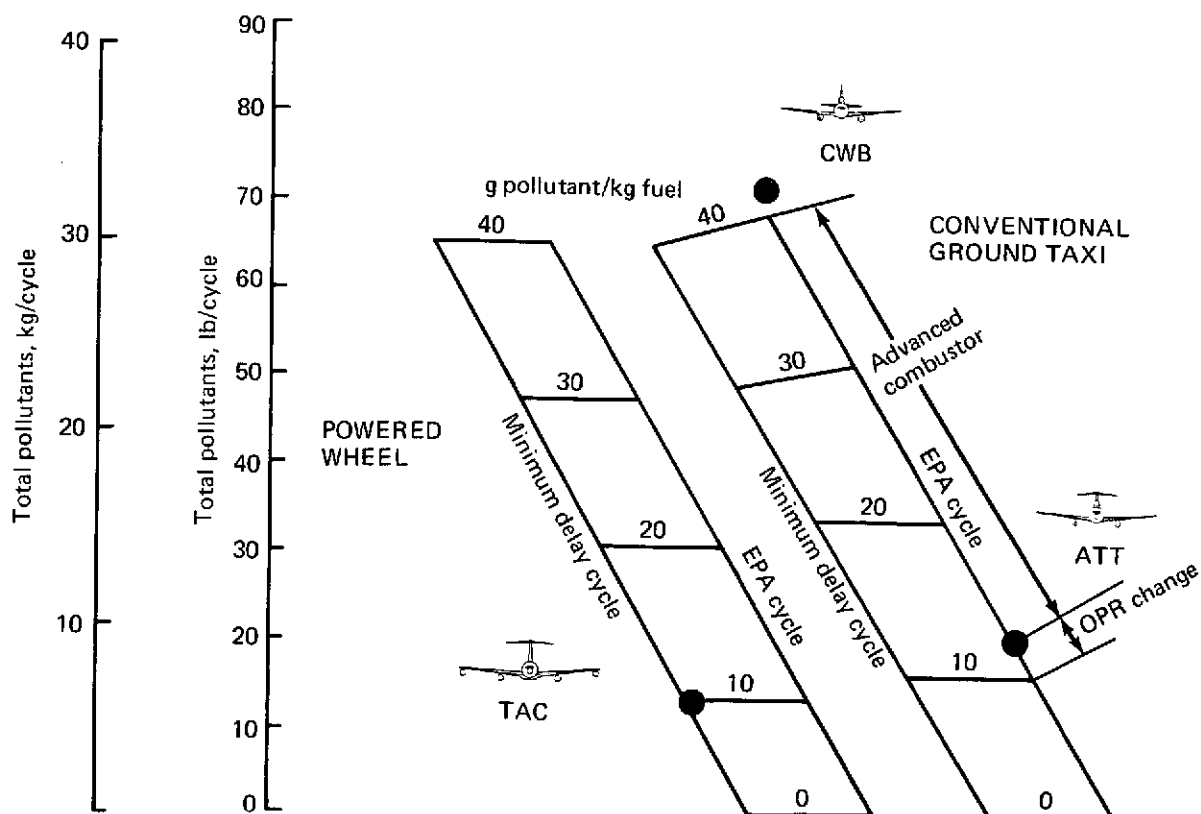


FIGURE 60.—TERMINAL-COMPATIBILITY BENEFITS—
OXIDES OF NITROGEN EMISSIONS

It is quite clear from the figure, of course that as engine-combustor technology improves, the gains to be realized either by improved delay or by use of the powered-wheel system become less and less significant. An important point in this regard, however, is that at least with respect to carbon monoxide, and as shown in figure 59 for hydrocarbons as well, a number of approaches exist to reducing the effective level of pollutant of the airplane in and around the airport.

The situation is different with respect to oxides of nitrogen pollutant which as shown in figure 60 allows very little flexibility whatsoever since no effective improvement is achieved by use of either powered wheel system or reduced ground congestion. The above points are of some importance when considered in light of anticipated combustor technology improvements. Current model tests show that often improvements to CO and HC are obtained at the expense of making NO_x more difficult to control, and vice versa.

7.1.3 Sensitivity and Trade Studies

7.1.3.1 Outboard Engine Position

The terminal-compatible (TAC) airplane was configured with outboard engines located at 85% of wing span in order to utilize the jet exhaust to encourage wing tip vortex dissipation. Since this spanwise location could not be selected based on existing analysis or test data, an appropriate but arbitrary position was selected during the preliminary design. Thus the present trade study was conducted to estimate the sensitivity of varying the outboard engine position. The impact on airplane configuration and flutter problems were looked at briefly.

Configuration Impact.—The baseline TAC wing with the engine at 85% span is gulled with six-degree dihedral on the inboard section and four-degree dihedral on the outboard section. Figure 61 shows the results of varying the engine location from 70% to 100% span while maintaining the inboard dihedral and body roll angle constant. As the engine is moved along the eleven-degree roll angle, the strut length is kept proportional to the wing chord. The resulting outboard wing dihedral angle is shown in the figure. This curve is based on the assumption of a vertical strut. However, beyond some spanwise location, it appears that engine attachment to the wing with a vertical strut would not be practical. This maximum outboard position limit was judged to be about 95% span. Outboard of this region, a horizontal strut attachment is considered. This installation would show a distinct reduction in dihedral from the vertical strut configurations. The figure shows two such potential engine installations at the wing tip.

A number of questions exist concerning the practicality of these configurations. Engine pod installations at the tip require different strut designs than the inboard installations. In addition, a horizontal strut at the tip would require different engine mounts than the vertical strut inboard; also, left and right wing struts would be required. The implications of these matters have not been addressed in detail.

Flutter Impact.—A brief flutter study was carried out to assess the effect of the extreme spanwise placement of the outboard nacelle on the TAC configuration. Since no mass or stiffness data was available for the TAC wing it was judged useful and expedient to carry out the investigation on a substitute wing developed during a previous Boeing study. A comparison of the main configuration parameters is given in table 11.

TABLE 11.—CONFIGURATION PARAMETER COMPARISON

Parameter	TAC wing	Substitute wing
Aspect ratio	9.0	8.6
1/4 chord sweep	35°	30°
Taper ratio	0.38	0.25
W/S (lb/sq ft)	113	119
t/c outboard	0.104	0.10
Engine bypass ratio	4	4
TOGW (approx), lb	310 000	420 000

Analyses were carried out with the outboard-engine strut mounted at 84%, 92%, and 100% span, keeping the vertical offset and the chordwise position relative to the leading edge constant (see fig. 62). At each location, variations of outboard strut stiffness were made. Two additional locations at 100% were also analyzed with the nacelle rigidly attached in the plane of the wing. In all cases, the inboard engine was located in its original position, 40% span, mounted on a strength-designed strut. For one location (100% strut-mounted), the effect of wing tip torsional stiffening was examined.

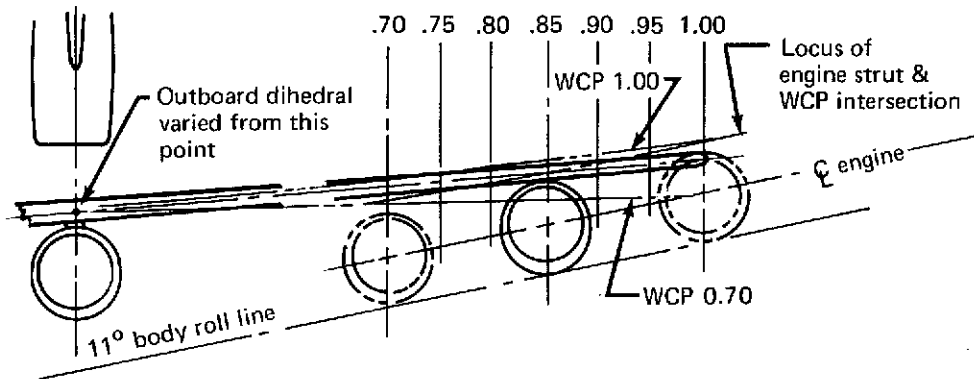
For each spanwise location of the outboard engine, flutter speed trends against outboard nacelle strut side and vertical bending frequency were established. From these, favorable strut frequencies were chosen, and a flutter speed determined. For the 100% span outboard engine location, two wing-tip torsional stiffening schemes were considered.

The results of this study are summarized in figure 63. It appears that for nacelle locations in the region of 85% to 90% the required flutter speed can be achieved by stiffness-designed struts without any added wing weight for flutter. The empty-fuel case is critical, and the flutter mode is symmetric. The flutter-speed trend is fairly flat up to 92% span but is degraded for 100% and the flutter mechanism appears to change from that at 92%. The region between 92% and 100% has not been explored and since the mechanism has changed the points cannot be joined. Much lower flutter speeds are experienced at 100% if the engines are rigidly mounted in the wing plane. Wing-tip torsional stiffening was not effective in increasing flutter speed for the 100% location.

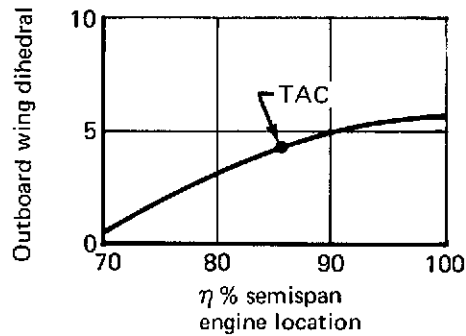
7.1.3.2 APU-Size Trade Study

The secondary power system defined for the TAC airplane placed heavy emphasis on the use of APUs to minimize operating restrictions on the main engines. Subsequent economic analysis showed considerable penalty for such a design approach. In the APU-size trade study, system configurations were considered which extracted more of the secondary power from the main engines, and the impact on emissions, noise, performance and airplane weight was calculated.

a) INFLUENCE OF OUTBOARD ENGINE LOCATION ON WING DIHEDRAL



b) OUTBOARD DIHEDRAL ANGLE VS WING SEMISPAN LOCATION



c) POTENTIAL WINGTIP-MOUNTED ENGINE INSTALLATION

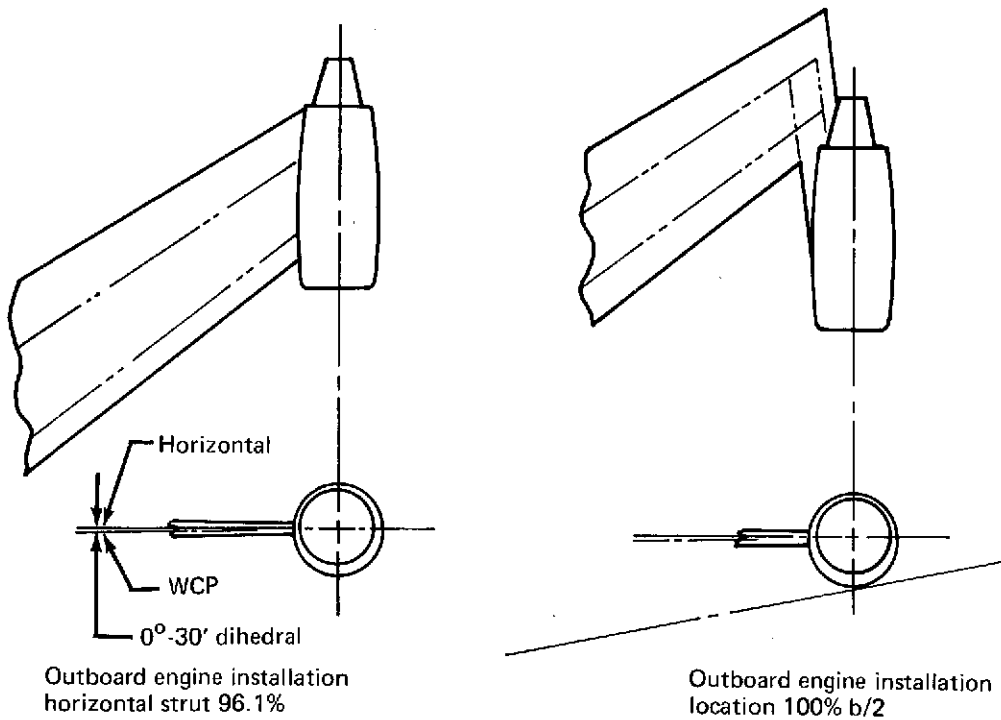


FIGURE 61.—CONFIGURATION IMPACT OF SPANWISE OUTBOARD ENGINE LOCATION

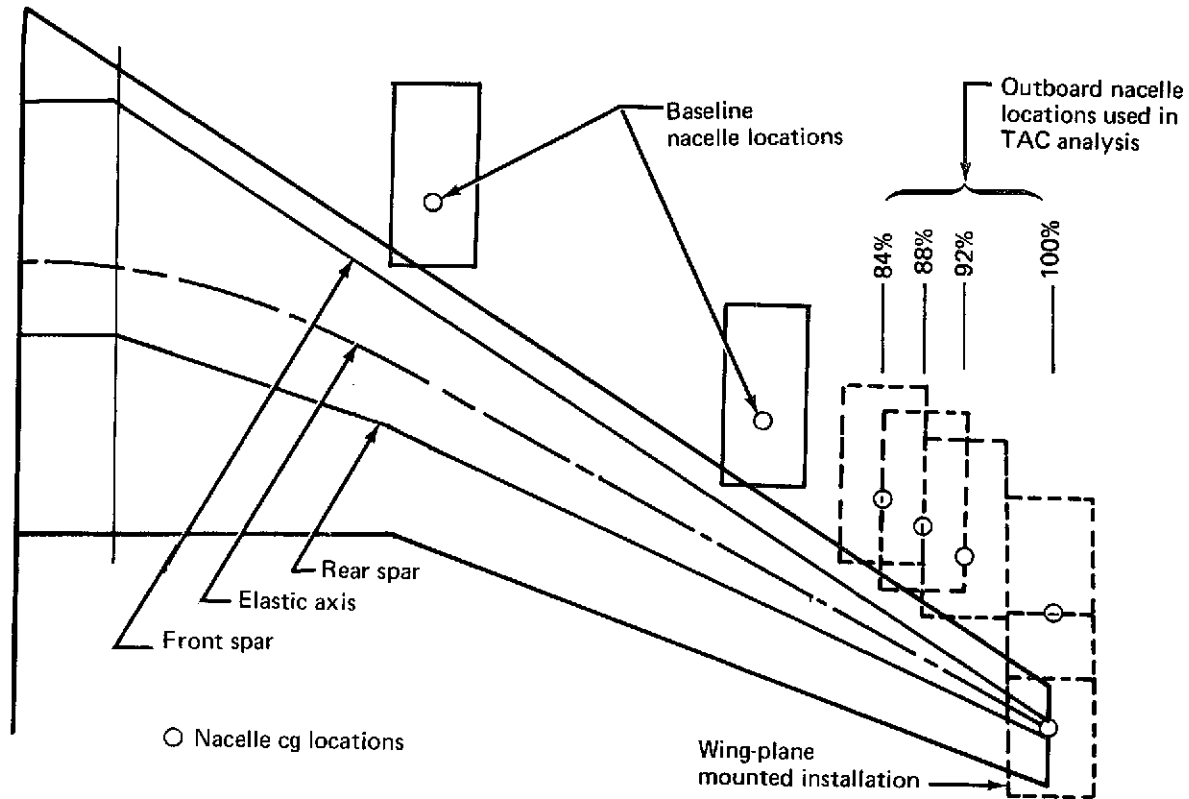


FIGURE 62.—NACELLE CONFIGURATIONS CONSIDERED IN FLUTTER ANALYSIS

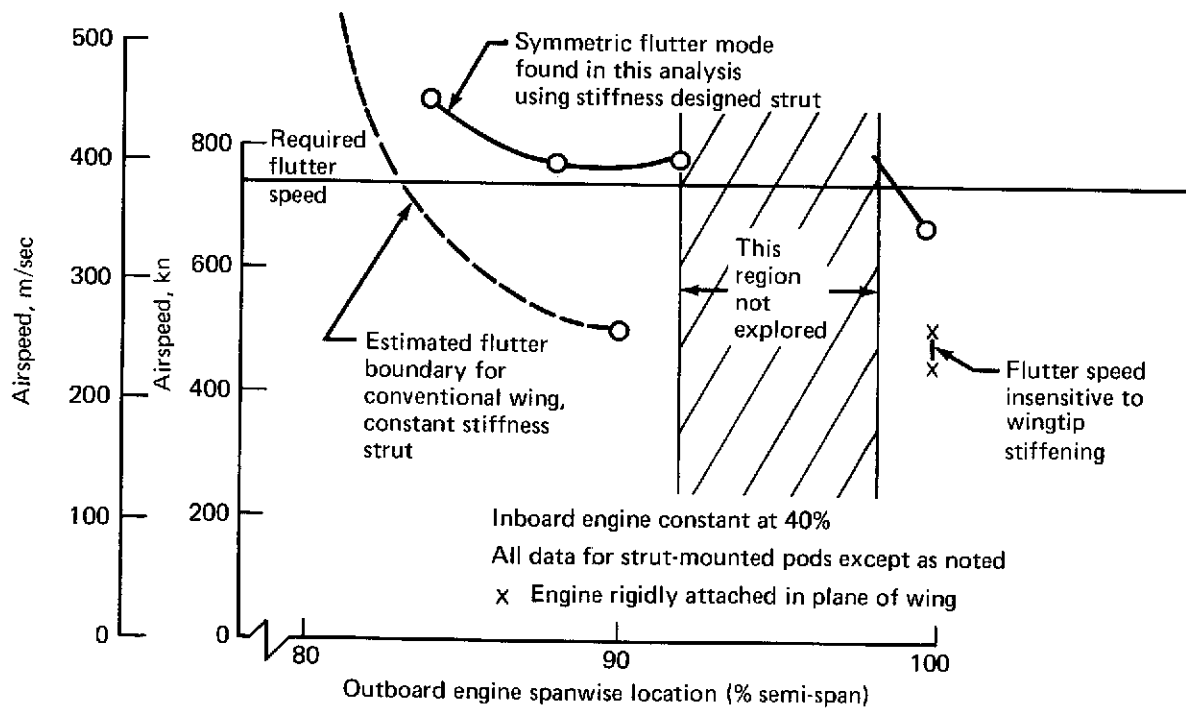


FIGURE 63.—RESULTS OF FLUTTER ANALYSIS

The results of this trade study are summarized in table 12 and discussed briefly below:

Design Characteristics.—In the TAC airplane, all pneumatic, hydraulic, and electrical power, including thermal anti-icing of the wings and engine inlets and powered wheels for taxiing, is provided by two large APUs, except that two of the four redundant channels of essential electrical and hydraulic power are powered by generators and pumps on the two inboard engines. In variation 1, engine inlet-anti-icing is done by bleed air from the engines, allowing appreciable reduction in APU size. In variation 2, all inflight power is provided by the main engines, and a single APU is used on the ground for secondary power and powered wheels.

Secondary Power System Weight.—The large reductions in APU weight for variations 1 and 2 are partly offset by increased weight of ducting, precoolers, and additional generators, pumps, and distribution lines.

Fuel Weight.—The same mission and taxi cycle are assumed for all three systems. The differences in fuel weight are due to APU and main engine SFC changes.

Noise.—The engine thrust in variation 2 is decreased due to the power extraction for secondary power, leading to a longer takeoff roll and lower climb gradient. This gives a slightly higher noise level under the climb path. On approach, *only* when there are icing conditions, the bleed air requirements of variations 1 and 2 require higher throttle settings; with no change in drag device size, this reduces the allowable descent angle of the upper segment of the two-segment approach. Also, the higher thrust setting increases the source noise, hence the noise level on the ground even during the lower segment below the 152 m (500-ft) transition altitude, as tabulated.

Emissions.—The CO emitted by the APUs during the taxi is strongly dependent on the percentage of full power at which they operate, giving less CO for the smaller APUs.

Total Weight.—The changes in TOGW were calculated for the change in equipment and fuel weights.

Direct Operating Cost.—The reduction in DOC is primarily due to reduced maintenance cost for fewer and smaller APUs.

7.1.3.3 Implications of Terminal Compatibility With Respect to Energy Conservation

It was not a specific requirement of the current study to evaluate the implications of aircraft energy use. Nevertheless, the question is of considerable current interest. In addition, some of the calculations developed for other reasons under this study, bear on the fuel usage. These miscellaneous points have been documented for future reference in this section.

TABLE 12.—SUMMARY OF APU SIZE TRADE STUDY

Item	TAC airplane	Variation 1	Variation 2
Design characteristics			
Number of APUs	2	2	1
APU power (each), kw(hp)	1348 (1810)	939 (1260)	939 (1260)
Engine inlet TAI	APU	Bleed air	Bleed air
Wing TAI	APU	APU	Bleed air
In-flight electric & hydraulic power	APUs + two engines	APUs + two engines	Four engines
Secondary power system weight			
Total APU weight, kg (lb)	2118 (4670)	1743 (3845)	887.6 (1957)
Pneumatic Δ weight, kg (lb)	0	-164 (-363)	+231 (+510)
Electrical Δ weight, kg (lb)	0	0	139.6 (+308)
Hydraulic Δ weight, kg (lb)	0	0	95.2 (+210)
Total Δ weight, kg (lb)	0	538.8 (-1188)	764.3 (-1685)
Fuel weight			
APU power setting—taxi, %	33	50	100
APU SFC—taxi	0.70	0.60	0.55
APU fuel—taxi, kg (lb)	139 (308)	119.7 (264)	109.7 (242)
APU SFC—cruise	0.45	0.55	—
APU fuel—cruise, kg (lb)	714.3 (1575)	873.1 (1925)	0
Δ engine SFC—cruise, %	0	0	+2.25
Δ engine fuel—cruise, kg (lb)	0	0	789 (+1740)
Total Δ fuel, kg (lb)	0	138.7 (+306)	44.9 (+99)
Noise			
Δ takeoff thrust, %	0	0	-1.65
Takeoff noise increase, dB	0	0	0.5
Approach thrust (icing conditions), %	6	15	20
Descent angle (icing conditions), deg	9	7.5	6.6
Approach noise increase (500 ft), EPNdB	0	2-4	3-6
Emissions			
CO—taxi, kg (lb)	12 (27)	6 (14)	3 (6)
HC, NO _x —taxi	Negligible	Negligible	Negligible
Total weight			
Δ TOGW due to equipment weight, kg (lb)	0	754 (-1663)	1070 (-2359)
Δ TOGW due to fuel, kg (lb)	0	324 (+715)	105 (+231)
Total Δ TOGW, kg (lb)	0	429 (-948)	965 (-2128)

Block Fuel Usage.—Figure 64 compares total block fuel expended for the design range at full payload for the four-study airplanes. As shown, the TAC airplane shows about a 5% improvement relative to the ATT design.

This improvement results primarily from the higher range factor due to better cruise lift-to-drag ratio of the high-aspect ratio wing. Other, but smaller, contributing effects include a reduction in ground fuel usage due to the powered wheel and an SFC improvement because of a four-engine-on-wing rather than center-engine-S-duct arrangement.

The point of interest is this. Design techniques different from today's may be used to advantage as fuel consumption becomes of increased interest as a figure of merit.

Energy Versus the Environment.—Figure 65 illustrates a direct example of the typical conflict between energy requirements and environmental quality (in this case aircraft noise). As shown in the figure, the use of increasing levels of acoustic treatment carries with it successively increased block fuel penalties. The curve has a significant knee in it which is associated ultimately with losses due to a large number of acoustically-treated inlet rings and fan duct splitters.

It is seen though that the higher levels of penalty can approach increments of 10 to 15% relative to a nontreated installation. This fuel loss is of particular interest in relation to the findings of the current study. It has been shown that noise reduction achieved by improved flight path capability can be made equivalent to that achieved by acoustic treatment. However, in the latter case, the drain on the nation's fuel reserves are increased whereas this does not occur for the first method.

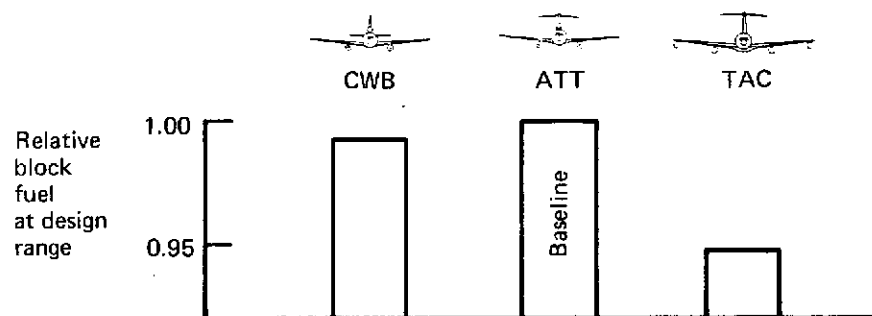


FIGURE 64.—RELATIVE FUEL USAGE OF THREE STUDY AIRPLANES

In the case of congestion, rather than conflict, design improvements can also considerably reduce fuel usage. Figure 66 illustrates the expected fuel usage for a 1850 km (1000 nmi) trip for two of the study airplanes. The comparison illustrates the 9.5% fuel savings which might be achieved by the TAC airplane if its projected delay improvements were realized. This can amount to savings on the order of three-quarters of a million gallons per year per airplane.

Again, the above fuel usage information was developed incidentally to the principal contract objectives. A detailed analysis of potential design improvements for reduced energy usage has not been attempted. Some potential design approaches which could be usefully explored are given in figure 67.

7.1.3.4 Wing Aspect Ratio

Summary.—The choice of the rather high $AR = 9.0$ for the TAC airplane was based upon low-speed considerations only. To verify that a somewhat lower AR would not appreciably affect the overall sized airplane characteristics an $AR = 8.3$ airplane has been analyzed. The results show that the $AR = 8.3$ airplane is about 1% heavier to do the same mission.

Discussion.—The choice of an aspect-ratio 9.0 wing for the TAC advanced-technology airplane was based on low-speed aerodynamic performance trends established in a preliminary task II study using the ATT airplane. In that study only low-speed performance effects resulting from selected changes were estimated without any consideration of overall mission performance implications. The aspect ratio increase from 7.6 for the baseline ATT airplane, to 9.0 for the TAC airplane was then aimed at reducing takeoff noise by increasing height over the community, reducing cutback thrust setting and reducing approach speed. Since the aspect ratio had been selected somewhat arbitrarily, that is an aspect ratio high enough to do the low-speed performance job but without consideration of the overall performance-sized airplane effects, the present sensitivity study was conducted to determine if the TAC airplane would be improved with an aspect-ratio 8.3 wing rather than 9.0.

The aspect ratio 8.3 airplane was derived from the TAC airplane accounting for changes resulting from the decrease to 8.3. Specifically, the high-speed polars were adjusted for the change in the induced-drag term; the low-speed polars were adjusted according to preliminary design estimates. Changes were also made to the weights data reflecting the wing and tail planform changes. No changes were made to the flight controls, acoustics and propulsion input data. The thumbprint sizing program was used to determine the airplane characteristics incorporating the aerodynamics and weights input data. The airplane was sized to the same design constraints and objectives as the TAC. These are restated following:

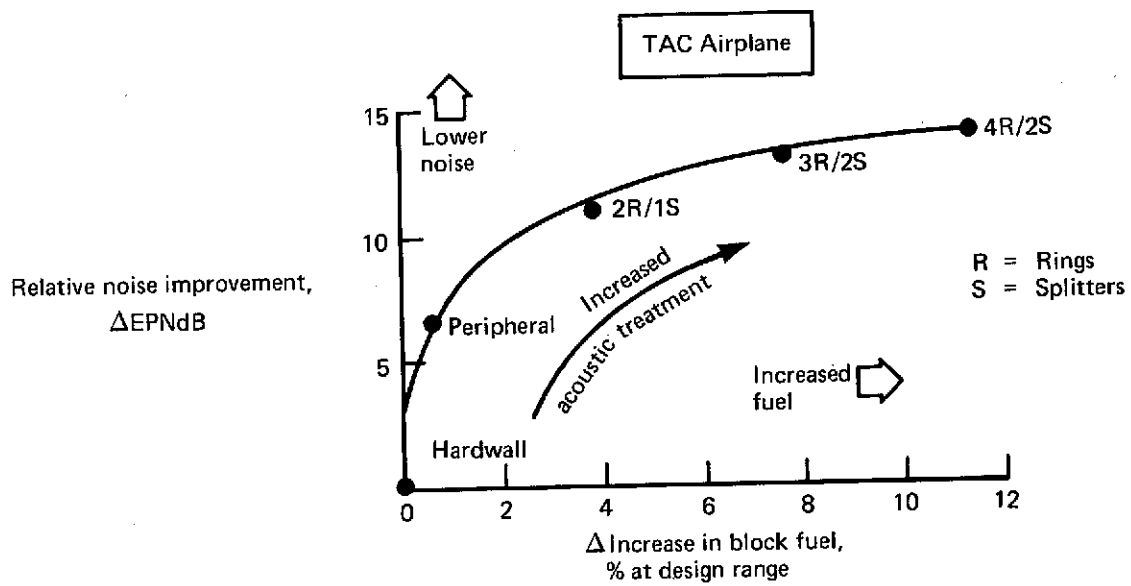


FIGURE 65.—ENERGY IMPLICATIONS OF NOISE REDUCTION

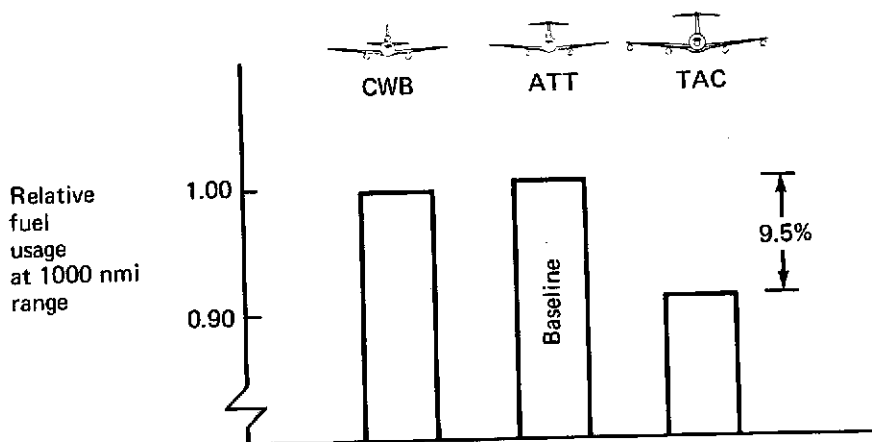


FIGURE 66.—FUEL-SAVING POTENTIAL DUE TO DELAY REDUCTION

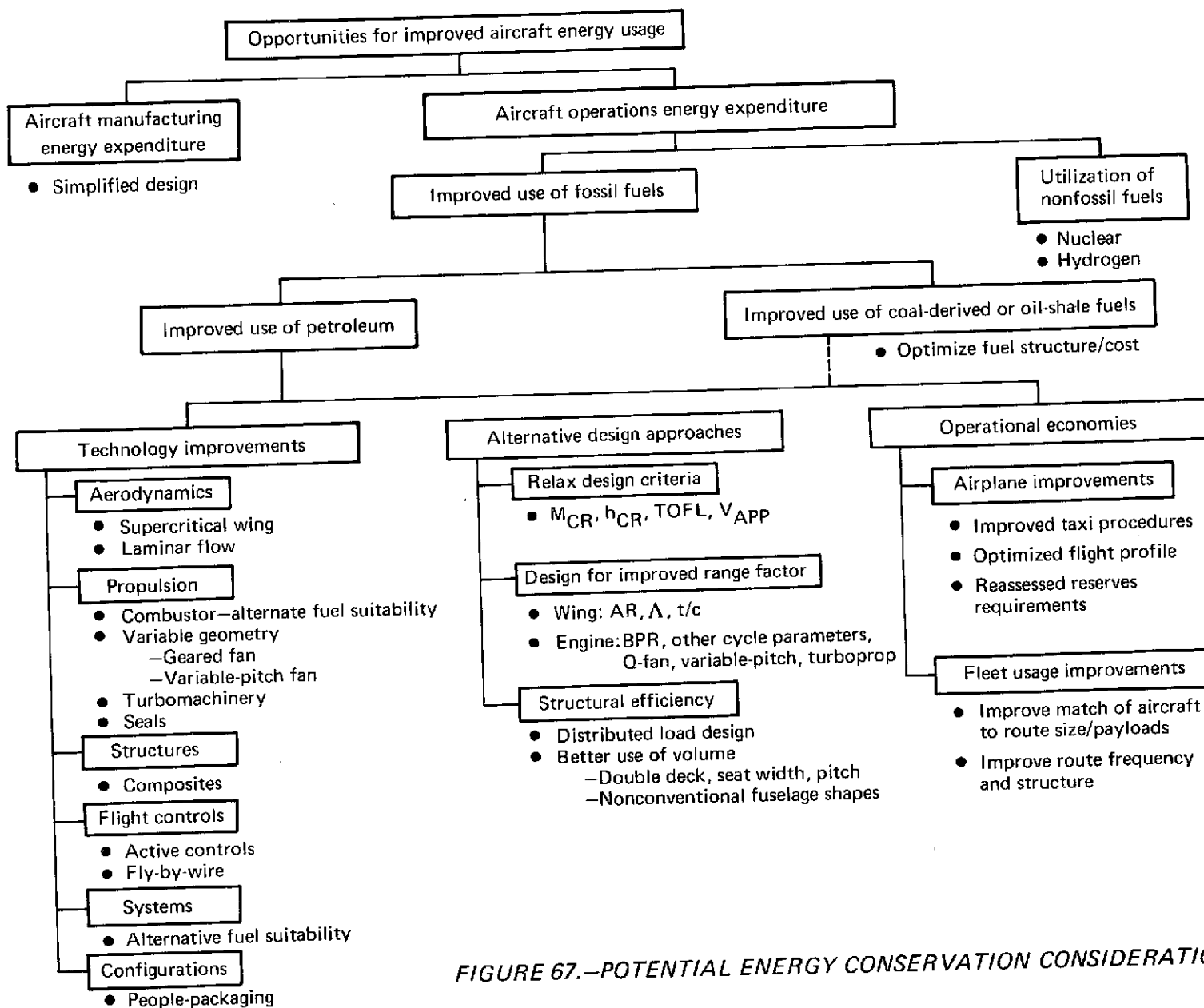


FIGURE 67.—POTENTIAL ENERGY CONSERVATION CONSIDERATIONS

Payload/range	5560 km (3000 nmi) still air with 18 140 kg (40 000 lb) of mixed class passengers and baggage and no cargo. (The quoted range does not include en route navigation, wind, or maneuver allowances.)
Cruise speed	0.90 Mach number
Initial cruise altitude	10 700 m (30 000 ft) at a temperature of ISA +10°C
FAR takeoff field length (1000 ft altitude/90°F day)	2530 m (8300 ft)
Landing approach speed	120 KEAS with full mixed-class passengers and baggage plus reserves

An additional constraint was that takeoff and approach noise for this airplane was to be equal to that of the TAC airplane.

The performance and geometry characteristics of the aspect ratio 8.3 airplane, are summarized in the table 13. For comparison the corresponding data for the TAC aspect ratio 9.0 airplane are also shown. Takeoff gross weight has increased approximately one percent for the aspect ratio decrease from 9.0 to 8.3. Cruise sizing, the combined effect of high-speed lift-to-drag ratio and CEW changes resulted in nearly a standoff. The degraded landing speed required an increased wing area which was responsible for the TOGW increase.

Based on this study, the TAC airplane configured with an aspect ratio 8.3 wing pays approximately 1% penalty in TOGW relative to a similar airplane configured with an aspect ratio 9.0 wing. However, an in-depth study would have to be made to establish the optimum aspect ratio for a TAC airplane.

7.2 ECONOMIC ASSESSMENT

7.2.1 Overview

The four airplanes developed in this contract were studied to evaluate operating costs, return on investment and net present value. In addition estimates were made, separately, for each of the design modifications incorporated into the baseline ATT airplane to improve terminal compatibility.

TABLE 13.—ASPECT RATIO STUDY—AIRCRAFT CHARACTERISTICS

Item	TAC (aspect ratio 9.0)	TAC modified to aspect ratio 8.3
Cruise speed, Mach	0.9	0.9
Payload/range	← Same as TAC on table 8 →	
Configuration		
Takeoff gross weight, kg (lb)	141,100 (311,100)	142,800 (314,900)
OEW/TOGW	0.554	0.550
T/W	0.299	0.298
Wing area, m ² (ft ²)	239 (2570)	258 (2770)
Sweep, rad (deg)	0.637 (36.5)	0.637 (36.5)
Performance		
Takeoff field length	Same as TAC on table 8	
Approach speed	Same as TAC on table 8	
Initial cruise altitude, km (ft)	11 800 (38 800)	11 700 (38 500)
Cruise L/D	14.90	14.54
Block fuel/payload	2.01	2.07
Range factor, km (nmi)	2010 (10 850)	1962 (10 600)
Community noise (est/est -FAR Part 36) using FAR abatement procedures		
Takeoff noise (cutback), EPNdB ^a	88.2/-15.0	88.3/-15.0
Sideline noise, EPNdB	90.3/-15.8	90.3/-15.9
Approach noise, EPNdB	97.9/-8.2	98.1/-8.0
Traded noise, ΔEPNdB	-10.2	-10.0

^aSee table 8

The technical characteristics of the study airplanes have previously been described in section 7.1.1. The various terminal compatibility design modifications were individually discussed in section 6.3.

In addition to an assessment of costs, the potential benefits of reduced congestion were evaluated. Relative to standard operating times as defined by the ATA cost formula, incremental operating times associated with airborne delay were evaluated. Expected delay levels judged to be encountered in actual practice were defined based upon the task II studies. The economic implications of expected versus standard delays were developed.

Figure 68 shows the percentage increase in DOC as the various modifications are made to the baseline ATT airplane under standard operating conditions. The TAC modifications have been grouped by type to show increased DOC as follows:

Congestion-relieving modifications	+3.3%
Noise-abatement modifications	+4.2%
Emission-reduction modifications	+1.9%

Similar data are shown on the right side of the chart for Net Present Value (NPV) of the investment. The impact on NPV shows different percentages from those of DOC since the amount of the investment in each modification varies. The emission control changes reduced NPV by 4.1%, noise abatement by 8.2%, and congestion reduction modifications, including the change to four engines, by 8.9%. These are calculated under expected operating conditions and are calculated to be 31% higher than ATT under the expected operating conditions. Figure 68 also indicates that, using either DOC or NPV as a criteria, ATT is a better investment if both airplanes operate with standard delay.

Standard delay, established in the 1967 ATA formula, consists of 14 min of taxi time (taxi-in and taxi-out) and six min of air maneuver. This standard is consistent with the no delay cycle of emissions studies. TAC is estimated to be able to achieve this standard in the 1980-2000 time period in all but completely saturated situations. ATT and CWB were assumed to be delay-equivalent, averaging 36 min of airborne delay each. Taxi time for all airplanes was left at 14 min for calculation inasmuch as this study did not undertake to study improvements in ground handling and terminal operations, nor did the study endeavor to estimate future ground delay under a do-nothing concept. The standard taxi time is known to be low for today's operations at busy airports.

When calculations of DOC and NPV are made for the baseline ATT under these expected operating conditions, DOC increases by 15.2% (6% above TAC at expected operating levels) and NPV decreases 52% (31% below TAC estimates).

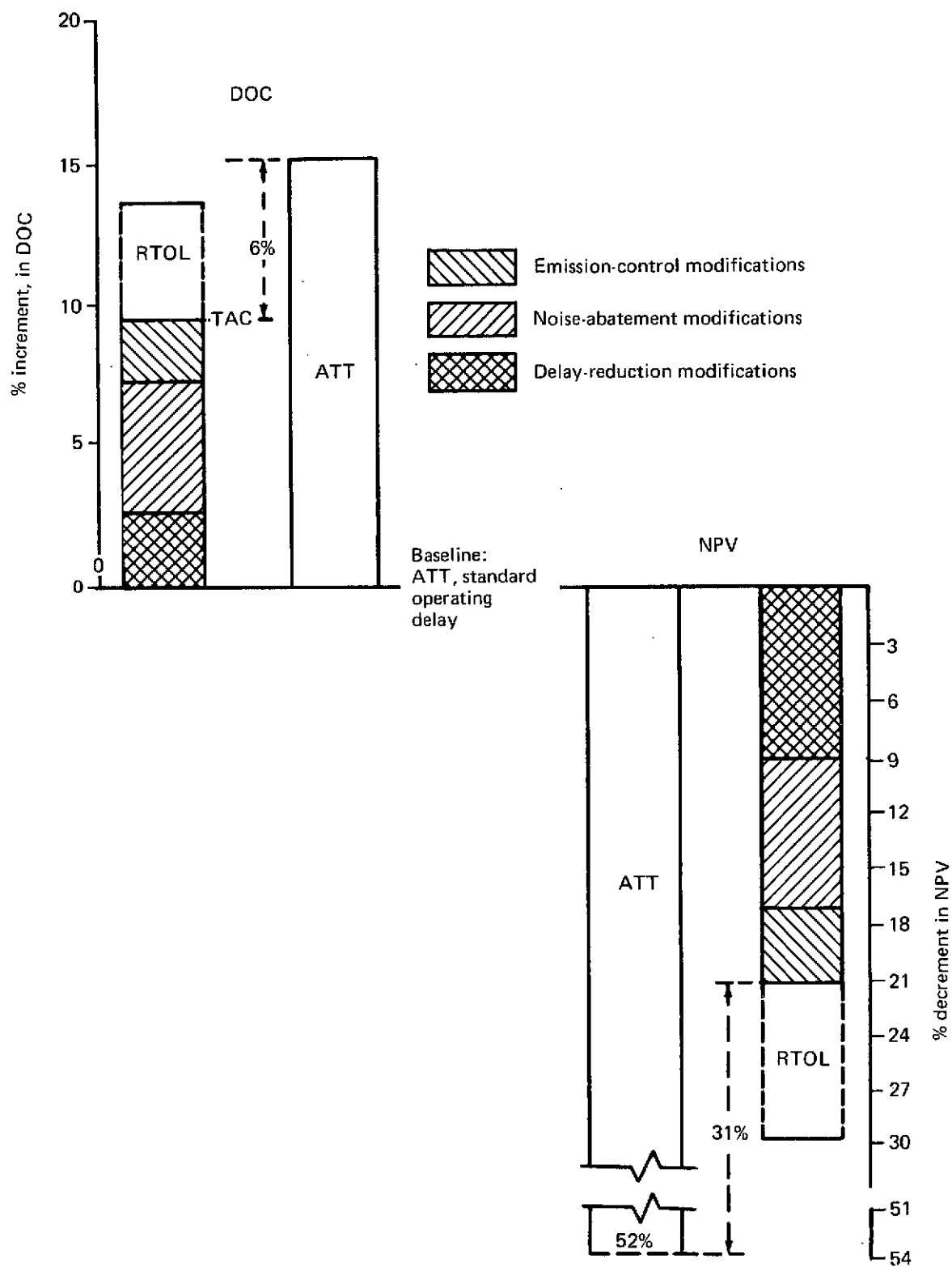


FIGURE 68—SUMMARY COSTS OF TAC MODIFICATIONS EXPECTED—
OPERATIONAL LEVEL

The conclusion is reached that with adequate Research and Development, and implementation the expected benefits of delay reduction methods have the potential to more than offset the increased cost of noise abatement and emission control as well as pay for the modifications necessary to achieve congestion reduction.

7.2.2 Methods

7.2.2.1 General

Figure 69 outlines the method used to assess the airline economics of airplanes involved in the study. The current wide body (CWB) was calculated by use of the updated ATA formula designed to evaluate present technology aircraft costs. However, the ATT and TAC airplanes include advanced technologies which do not readily adapt to the ATA formula and historical data. A complexity analysis was, therefore, made in order to determine acquisition price and maintenance cost corrections. Operating costs were calculated by the basic ATA formula. However, this formula was updated by Boeing to reflect present operating costs and modified to reflect the results of the complexity analysis.

7.2.2.2 Complexity Analysis

The airplane acquisition prices were developed using a computerized cost model based on a part-by-part analysis of the various airplane configurations. Historical data on airplane models 707, 727, 737, and 747, independent programs such as STOL, advanced composite flap and body programs, etc. were used to develop programs costs. Independent variables such as weight and area were basic to the cost analysis. Cost factors such as dollars per pound, dollars per square foot, were used in conjunction with the degree of complexity of each of the advanced technologies estimated. Table 14 indicates the estimated acquisition price from the ATT through each of the TAC modifications (Δ s) and finally to the total TAC airplane acquisition price. The additional modifications to the TAC aircraft for RTOL are calculated. CWB is also shown as a point of reference. Each modification was priced as a separate entity. For example an increase of \$57 000/airplane in acquisition price of the aircraft was calculated for locating outboard engines at 85% wingspan. The increase in price is due to requirements for increased wing structure and a larger empennage. Similar calculations were made for each modification as shown in table 15.

Figure 70 shows schematically the maintenance complexity analysis. Each airplane was studied on an ATA system category basis. Where similarity was found to systems for which historical data was available, comparisons were made and costs calculated based on differences in degree, size, weight, or other suitable criteria for the system involved. However, a number of systems would not lend themselves to direct comparison because of uniqueness involved in the advanced system. In

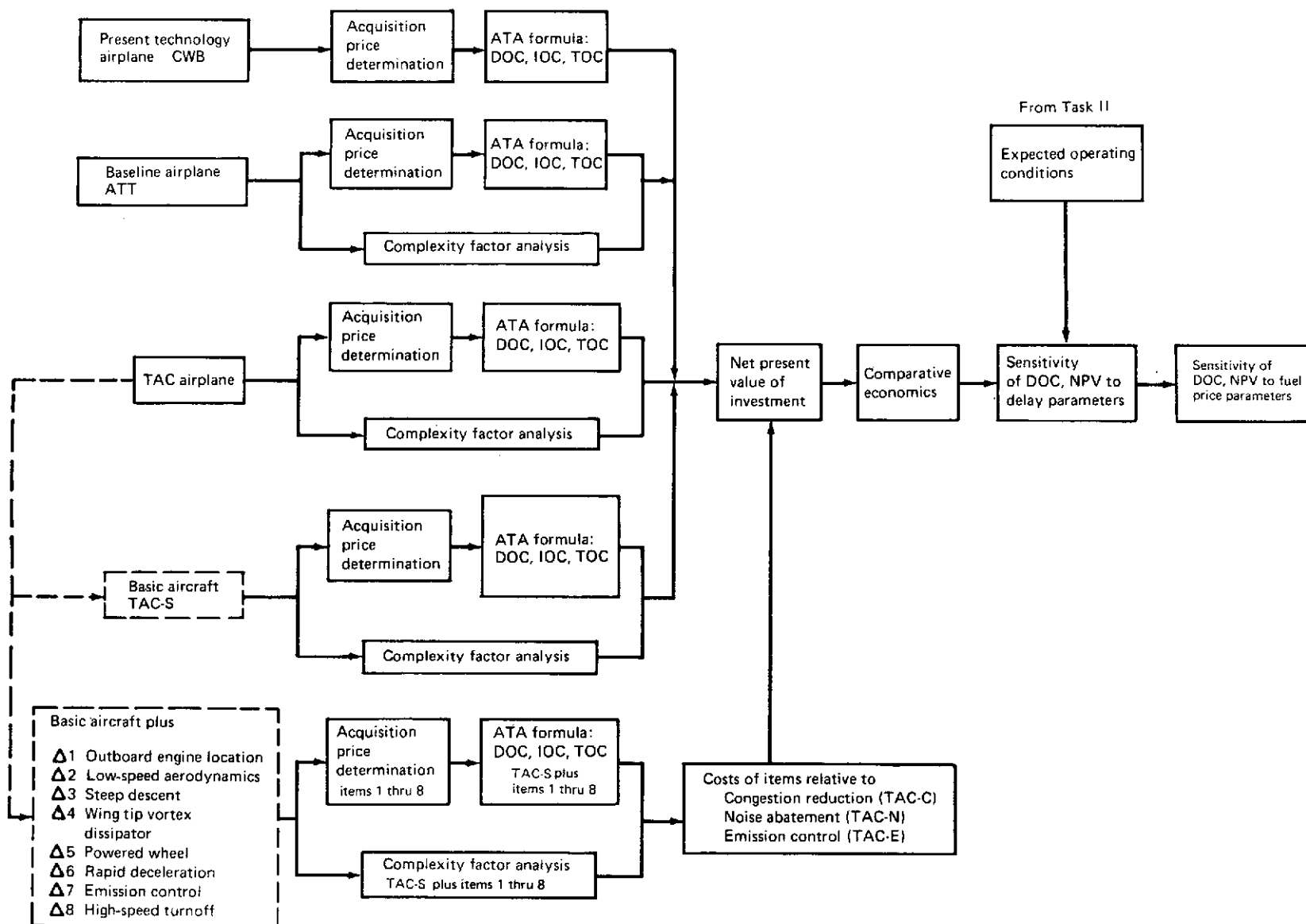


FIGURE 69.—ECONOMIC IMPACT EVALUATION METHODOLOGY

TABLE 14.—COMPLEXITY ANALYSIS: ACQUISITION COSTS

Item	300 aircraft estimate, millions of dollars 1972			
	Airframe	Engine	Spares	Total
Current widebody airplane (CWB)	12.80	2.28	1.45	16.53
Advanced technology airplane (ATT)	11.88	2.22	1.38	15.48
Basic TAC airplane TAC-S	11.99	2.54	1.47	16.00
+ Δ 1 (outboard engines)	12.05	2.55	1.47	16.07
+ Δ 2 (low-speed aerodynamics)	12.30	2.50	1.47	16.27
+ Δ 3 (steep descent)	12.27	2.57	1.49	16.33
+ Δ 4 (wingtip vortex dissipator)	12.06	2.54	1.47	16.07
+ Δ 5 (powered wheel)	12.19	2.52	1.49	16.20
+ Δ 6 (rapid deceleration)	12.01	2.55	1.47	16.03
+ Δ 7 (engine emissions)	11.99	2.54	1.47	16.00
+ Δ 8 (high-speed turnoff)	12.03	2.54	1.47	16.04
Terminal area compatibility airplane (TAC)	12.98	2.54	1.54	17.06
Reduced takeoff & landing TAC airplane (RTOL)	13.38	2.79	1.64	17.81

Facility costs and manufacturing research and development costs are not included.

TABLE 15.—ACQUISITION PRICE OF TAC MODIFICATIONS

Modification	Delta acquisition price, millions of dollars	Reason
Outboard engine location	0.057	Additional wing and empennage using composite materials
Low-speed aerodynamics	0.315	Weight increase of 2495 kg (5500 lb)
Steep descent	0.281	Additional structure for speed brakes; additional avionics
Tip vortex dissipator	0.071	Additional equipment and associated avionics
Powered wheels	0.198	Landing gear complexity
High deceleration	0.021	Landing gear complexity; avionics included
Engine emission control	0	Engine manufacturer estimate
High-speed turnoff	0.043	Nose gear complexity
Total delta acquisition	0.986	Avionics included
Price		

those areas, advanced research programs, study results, and expert opinion were used to estimate maintenance costs on these systems. This was done for each modification including effects on the airframe to accommodate the modification. For example, maintenance complexity analysis indicated an increase in direct maintenance costs of 13 cents/flight-hour on a 2-hr flight (11 cents material, 2 cents labor) for placing the outboard engines at the 85% wingspan point. This is because of slightly greater amounts of composite structure in the fuselage, wing and empennage resulting from the outboard movement of the engines. Similar calculations were made for all TAC modifications. Table 16 shows the results.

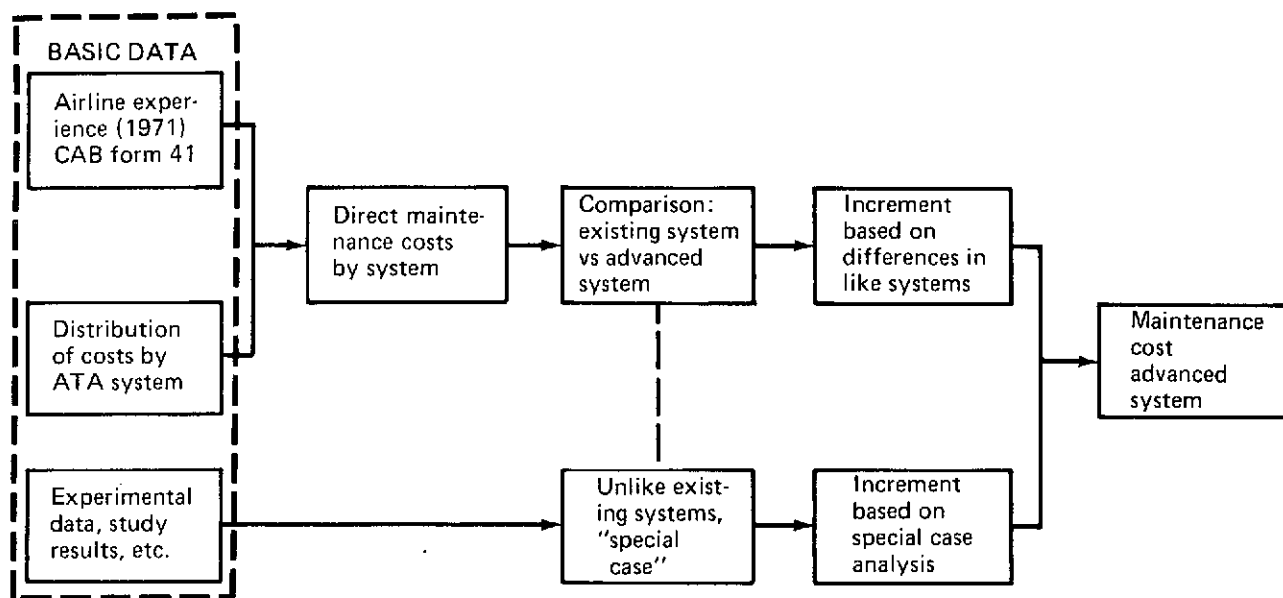


FIGURE 70.—COMPLEXITY ANALYSIS: MAINTENANCE COSTS

TABLE 16.—INCREASE IN TAC MAINTENANCE COSTS BY MODIFICATION

Modification	Delta maintenance costs, dollars per flight-hour/2-hr flight		
	Material	Labor	Total
Outboard engine location	0.11	0.02	0.13
Low-speed aerodynamics	0.66	0.19	0.85
Steep descent	4.12	10.70	14.82
Tip vortex dissipator	0.66	0.46	1.12
Powered wheels	3.23	6.78	10.01
High deceleration	0.46	0.64	1.10
Engine emission control	0	0	0
High-speed turnoff	0.21	0.30	0.51
Total	9.45	10.09	28.54

7.2.2.3 Return on Investment

Net Present Value (NPV) is a management decision-making tool that is used extensively for choosing among alternative investment opportunities. The NPV technique was selected for making economic comparisons in this study. This technique takes the estimated positive and negative cash flows resulting from (1) acquisition of revenue-producing property and (2) the operation of that property, and determines the value at time zero of those cash flows. Allowance is made for taxes and tax credits in accordance with the tax laws of the United States. The calculations acknowledge the greater value of an amount of money in pocket, due to investment return potential, compared to the same amount of money to be received in the future. All other risks being equal, those alternatives yielding highest NPV are preferred.

During this study, NPV was calculated by classical methods. A 10% discount rate was used in the evaluations in accordance with the Statement of Work. Depreciation for tax purposes was accomplished over 8 years, using sum-of-the-years-digits as the method of calculation. Seven percent tax investment credit was allowed in the calculations.

7.2.3 Operating Cost Calculation Results

7.2.3.1 Baseline DOC Calculation

Figure 71 shows the calculated DOC of the ATT. The build-up of costs in this study in contrast to the ATT study is indicated. The most significant increase from the ATT study calculations is due to modification of the basic ATA costing formula to more realistically reflect 1972 costs. The complexity analysis, relative to ATT, added smaller increments to the cost than did the revision of the formula. Figure 71 shows DOC in dollars per kilometer (\$/KM) on the left and in cents per available seat-kilometer (¢ASKM) on the right. Also shown are the conventional dollars per statute mile and cents per available seat-mile costs. Inasmuch as all compared aircraft have the same number of seats, there is no reason to make the additional calculations for seat kilometer (mile) costs. Therefore, all further DOC data is presented in dollars per kilometer (airplane mile) costs. The upper line in figure 71 is the baseline DOC for ATT.

7.2.3.2 Complexity Analysis of Maintenance

Each of the aircraft in the study were analyzed as described in section 7.2.2 to determine acquisition price and maintenance costs of the more advanced technology aircraft. Maintenance costs of seven ATA systems showed significant increase over present technology systems. Table 17 shows the high-leverage systems in terms of maintenance costs. The principal items of increased maintenance for ATT compared to present technology systems (CWB) are the advanced avionics and the composite structure (ATA Systems 34, 53, 55, and 57).

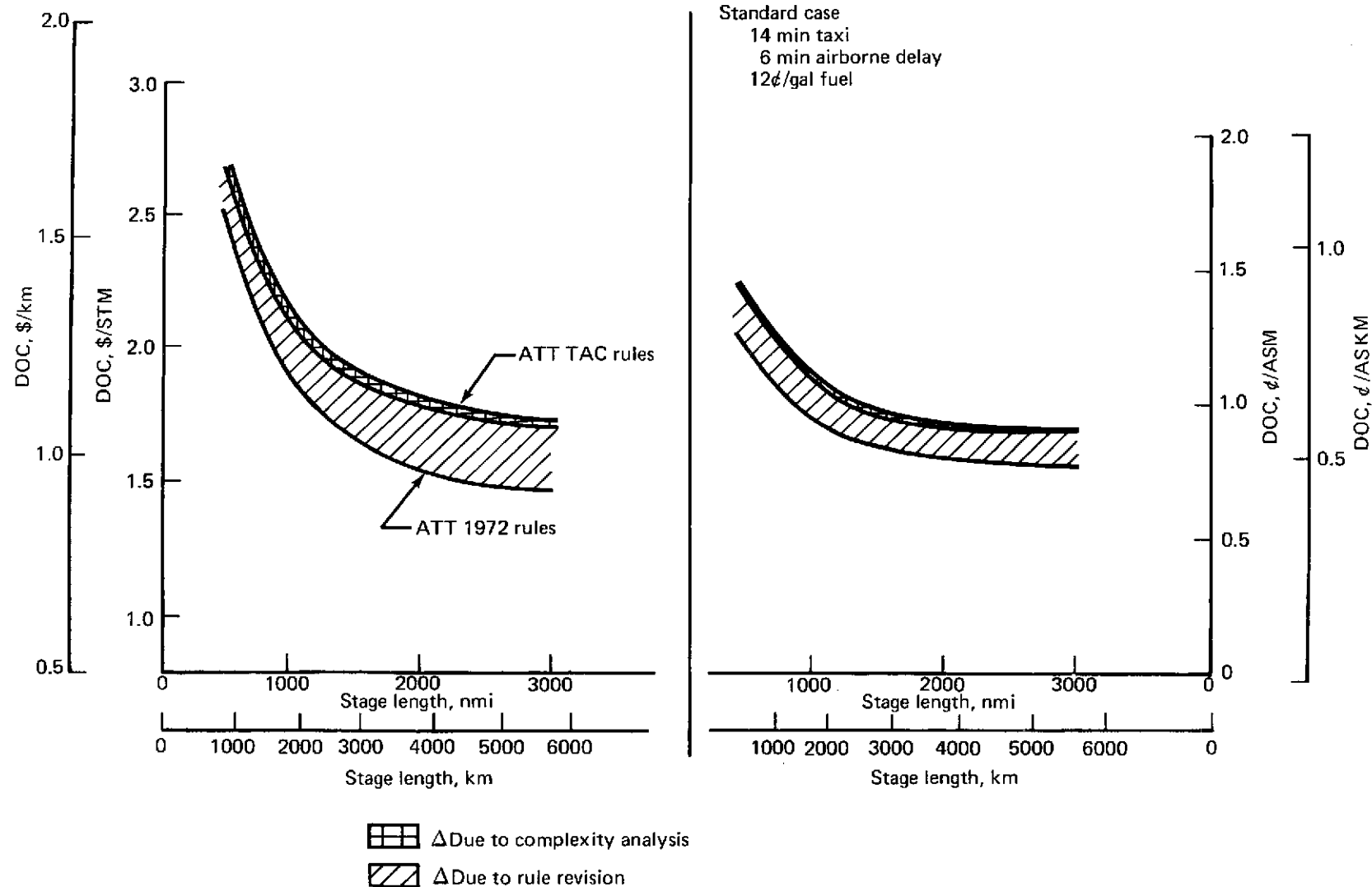


FIGURE 71.—ADVANCED TECHNOLOGY TRANSPORT DIRECT OPERATING COSTS

TABLE 17.—MAINTENANCE COMPLEXITY ANALYSIS

ATA system	Maintenance costs, dollars per flight-hour/2-hr flight (unburdened)			
	Present technology CWB	Advanced technology ATT	Terminal area compatibility TAC	TAC RTOL
27 flight control	5.76	5.76	7.10	7.10
32 landing gear	11.35	11.35	15.68	15.71
34 navigation	17.40	18.80	19.65	19.65
49 APU	3.24	3.24	23.20	23.20
53 fuselage	5.33	9.80	10.68	10.68
55 empennage	2.07	2.44	2.62	2.63
57 wing	3.50	5.10	6.18	6.21
Airframe total	95.06	102.39	131.44	131.54
Engine total	95.97	92.27	93.70	103.70
Maintenance total	191.03	194.66	225.14	235.24

The TAC modifications were made for more complex systems which were estimated to have relatively-high maintenance costs. Table 17 shows these systems and the estimated direct (unburdened) maintenance costs in dollars per flight-hour on an average two-hr flight. This figure indicates what systems escalate the maintenance costs shown in table 16. Landing gear (system 32) and APU (system 49) are the systems with the greatest increase. Both of these systems are involved with powered wheel and thus increase the costs of powered-wheel operations. Sixty-seven percent (67%) of the APU cost is allocated to the concept of using APUs as a source of secondary power instead of using the main engines. The remainder was allocated for operation of the powered wheel. The APU as a secondary power source is a noise-abatement procedure designed to permit throttle-back of the main engines on approach thereby reducing community noise.

Figure 72 shows the leverage the additional maintenance costs have on TAC operating costs. Crew costs, depreciation and insurance for TAC show nominal increase over the corresponding costs for ATT. Fuel consumption is lower for TAC than for ATT. Figure 73 shows the same data for the expected delay case in contrast to the standard delay of figure 72.

However, the TAC maintenance cost estimates are 26% higher than those for ATT on an 1850 km (1000 nmi) trip, and is the dominant factor in the 9.4% increase in trip costs shown. Figure 73 points up the need for research which will lower maintenance costs, particularly of the APU, if the concept of in-flight usage of the APU for secondary power is to be carried out. A 25% improvement in APU reliability would decrease DOC by 1%.

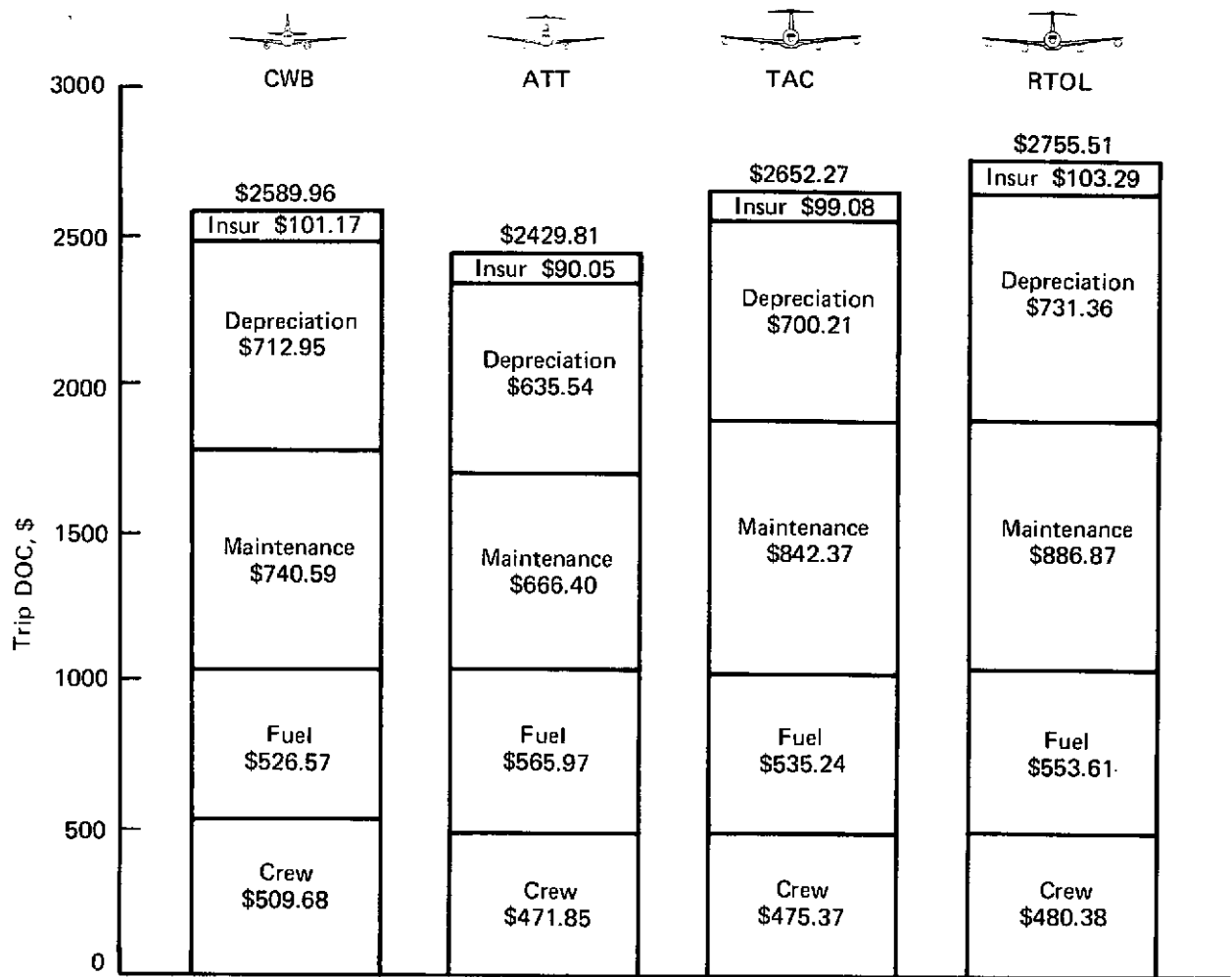


FIGURE 72.—COMPARATIVE DIRECT OPERATING COSTS—STANDARD CASE—1850KM
(1000 NMI) STAGE LENGTH

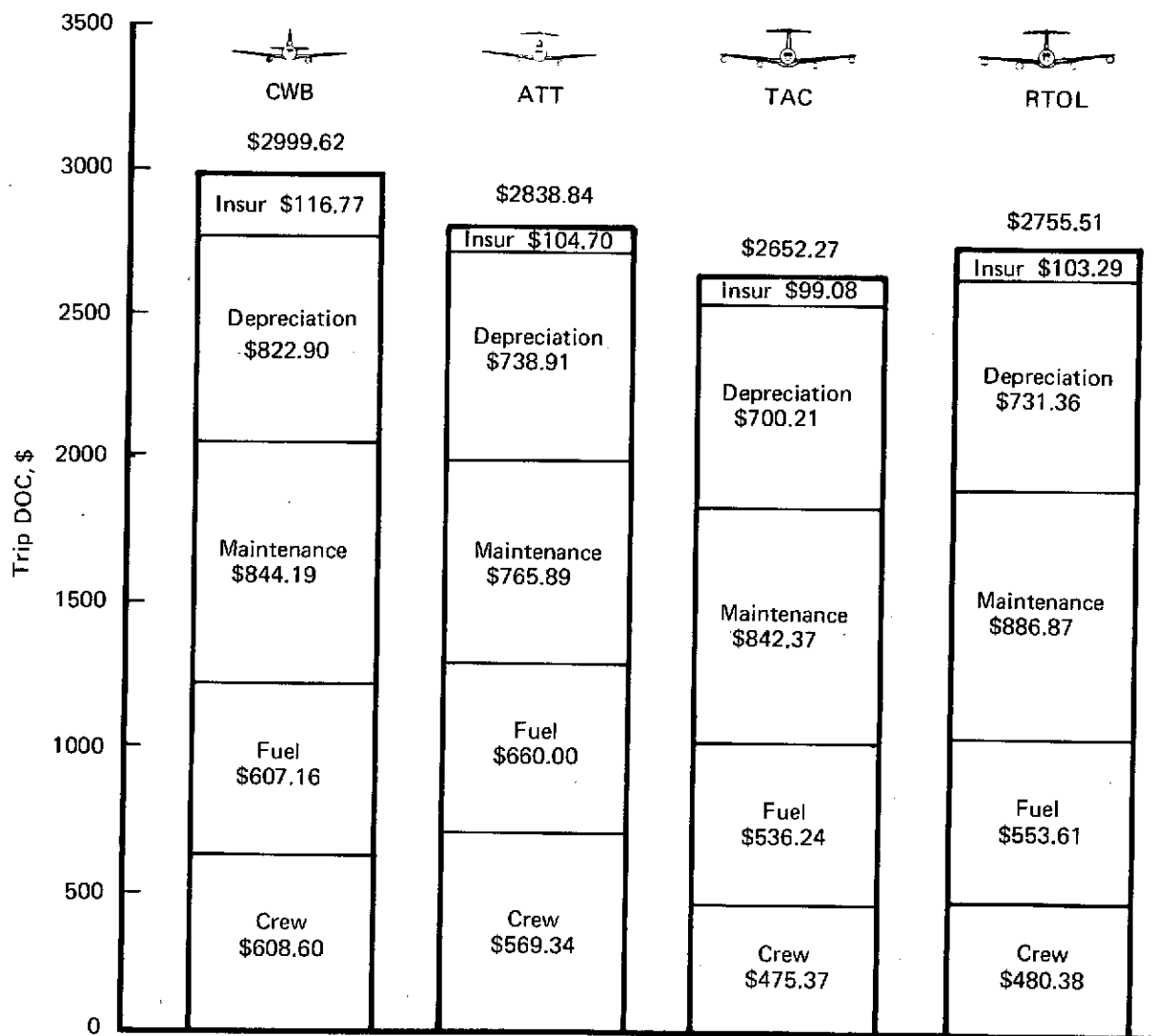


FIGURE 73.—COMPARATIVE DIRECT OPERATING COSTS—EXPECTED DELAY—
1850KM (1000 NMI) STAGE LENGTH

A conservatism in the above estimates should be noted. The avionics system includes an advanced type of maintenance monitor. It was included in calculation of acquisition costs, maintenance costs, etc. However, no credit was taken for any decrease in maintenance costs due to the operation of this monitor. This approach was taken because no data of statistical significance was available from which to estimate such benefits. If the monitor can reduce maintenance costs by 5% to 10%, the DOC saving would amount to 1.5% to 3.0%. These estimated benefits have not been used in making the calculations shown above.

7.2.4 Cost of TAC Modifications

Each modification to make the airplane more compatible with the terminal area was treated economically as a separate entity. This was done in order to be able to determine what items had high-cost leverage and which did not. Figure 74 shows the percent increment of DOC, above the baseline ATT under standard delay conditions, for each modification made to create the TAC aircraft. The sum of the modification increments equals 9.4% increase in DOC above the baseline.

When NPV is used as the criteria for determining the worth of investment in each aspect of the TAC concept, results are similar. NPV declines by 7.8% when the steep descent delta is evaluated; 3.5% for delta 5, the powered wheel. The other modifications show a small erosion of NPV. All data above refers to operations at 1850 km (1000 nmi) with 14 min of taxi, six min of air maneuver, and 12 cents per gallon fuel, the standard used for comparison.

7.2.5 Cost/Benefit of Congestion Reduction: Expected Operating Conditions

The data above shows economic comparisons for all airplanes operating under the same delay conditions (six min airborne delay and 14 min taxi time). This was done in order to compare costs under the same ground rules. However, the whole purpose of the TAC congestion reduction modifications was to get the benefits of reduced delay. The calculations above assume no such benefits.

Task II of the TAC study used a computerized simulation to calculate expected airborne delay as traffic increased in accordance with traffic projections. Conclusions were drawn as to what delay could be expected if improvements were not introduced. Conclusions were drawn with respect to expected delay with proposed aircraft modifications. Section 5.0 discusses these studies in detail.

This data has been used to determine the expected delay of the TAC airplane as a function of airplane movements at an airport. The shaded area of figure 75 represents the expected delay of the TAC airplanes as movements per hour increase. The TAC airplane is calculated to be able to hold delay to the standard six min of air maneuver for all situations up to 40 to 50 movements per hour per runway. Present technology data indicates a rapid build-up of delay as movements

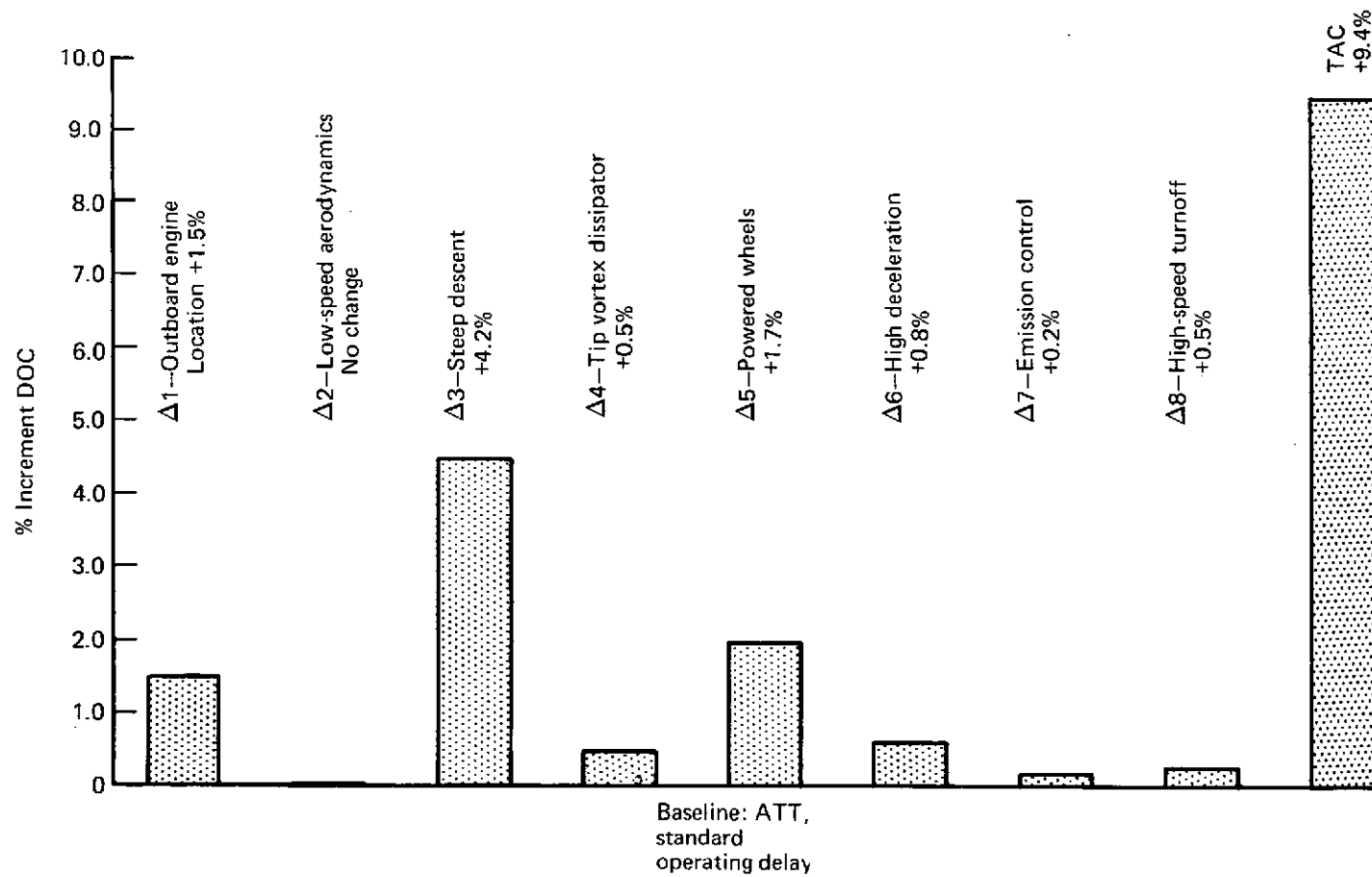


FIGURE 74.—DIRECT OPERATING COSTS OF TAC MODIFICATIONS—STANDARD CASE

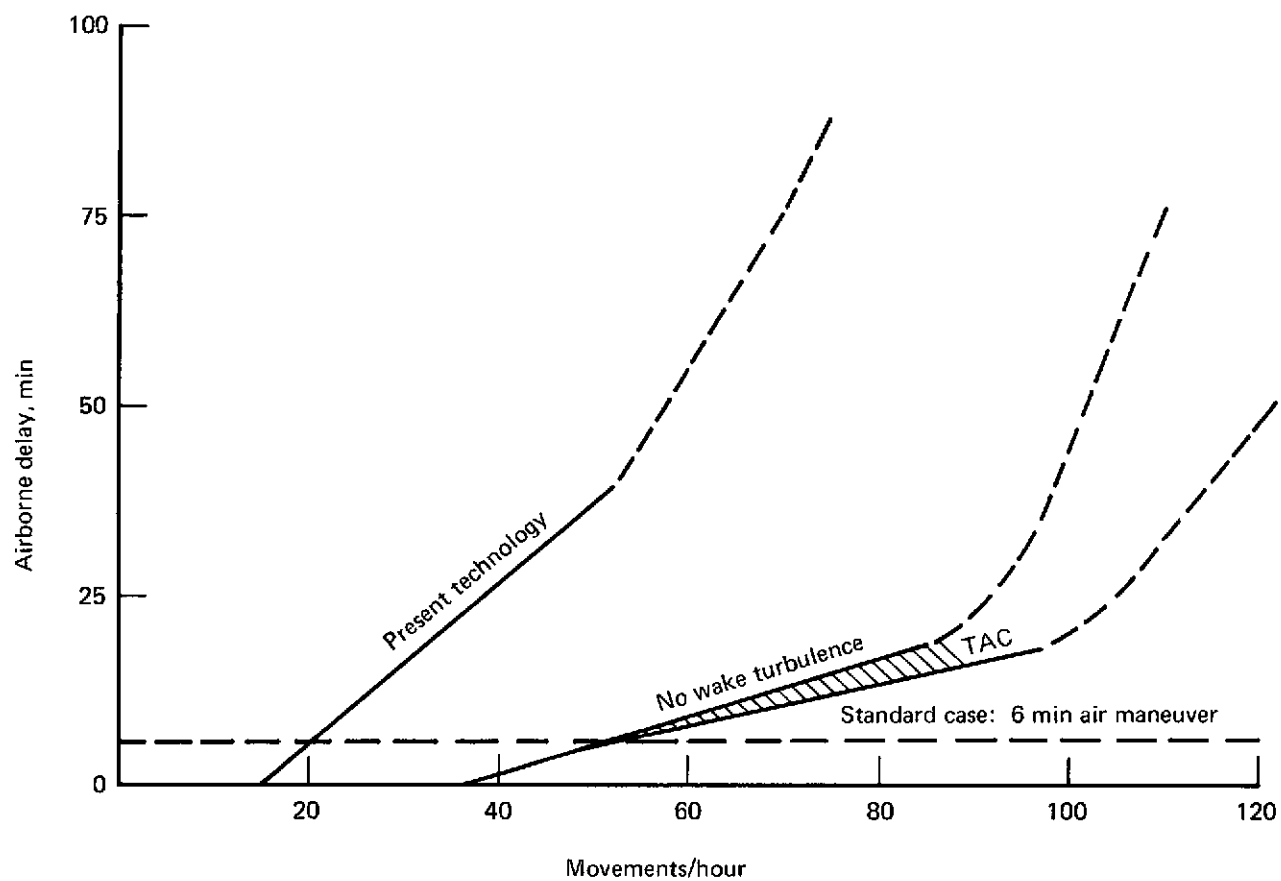


FIGURE 75.—VARIATION IN EXPECTED DELAY AS FUNCTION OF MOVEMENTS/HOUR

increase, reaching approximately 36 min for 40 to 50 movements per hour per runway as shown in figure 75.

The above data was used to establish expected operating conditions at 36 min of airborne delay if airline fleets are made up of present technology airplanes. If TAC type aircraft predominate the 1980-2000 airline fleets, the expected airborne delay would be six min. These estimates have been used to calculate costs under the expected operating conditions. Constant taxi time (14 min) was used for all calculations.

Figure 76 presents data showing the percentage of change in DOC, using ATT under expected operating conditions (36 min airborne delay, 14 min taxi) as a base. All models are shown under the expected operating conditions if that aircraft type is predominant in the 1980-2000 airline fleets. The TAC airplane will have a 6.7% lower DOC than the ATT under expected operating conditions for both aircraft; and 12% lower than present technology aircraft. The percentage change in Net Present Value, using the ATT under expected operating conditions as a baseline, shows similar results. TAC investment is calculated to be 33% better than ATT and 65% better than CWB when all operate under expected operating conditions.

The conclusion to be reached is that the delay reduction predicted for TAC-type aircraft will more than pay for the additional costs of acquiring and operating TAC airplanes. The reduction in delay, if achieved, more than pays for the cost of noise abatement modifications and emission reductions.

The reader should be aware of the level of confidence in various portions of the economic analysis. The additional costs of owning and operating TAC airplanes have been analyzed in detail. Estimation of the benefits of delay reduction are a reasonably high-confidence item. The only high-risk element is the accuracy of the estimate of delay reduction. If the airlines were to buy fleets of TAC-type aircraft and delay reduction proved to be less than estimated, airline costs would increase and returns on the investment would decrease. Yield (approximately the same as fare) increases would then be necessary if airlines were to receive the same return on investment as could be expected from investment in the ATT.

Figure 77 plots the increase in yield required in order for the airlines to get the same return on their investment as from an investment in ATT, plotted against Delta Delay. Delta Delay is the difference in airborne delay when fleets are made up of TAC airplanes compared to delay when fleets are made up of ATT. It shows a 5.5% yield increase is necessary if both aircraft have the same delay. It also shows that if TAC can reduce delay by 14 min, compared to ATT delay, the airlines would realize the same return with no change in yield. It also indicates that further delay reductions would make fare reductions possible. The chart can be entered with any Delta Delay

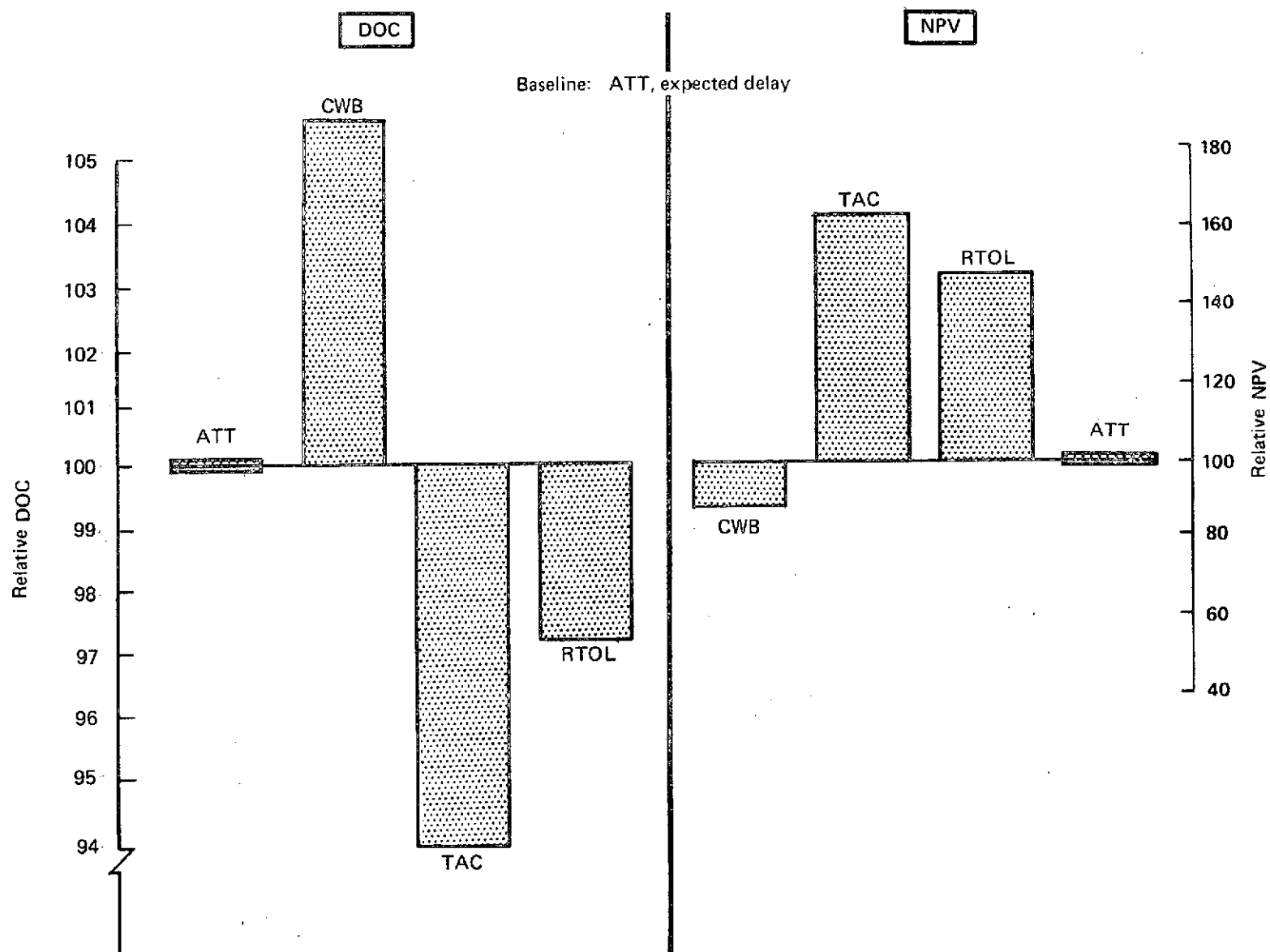


FIGURE 76.—ECONOMIC COMPARISONS—EXPECTED OPERATIONAL DELAY

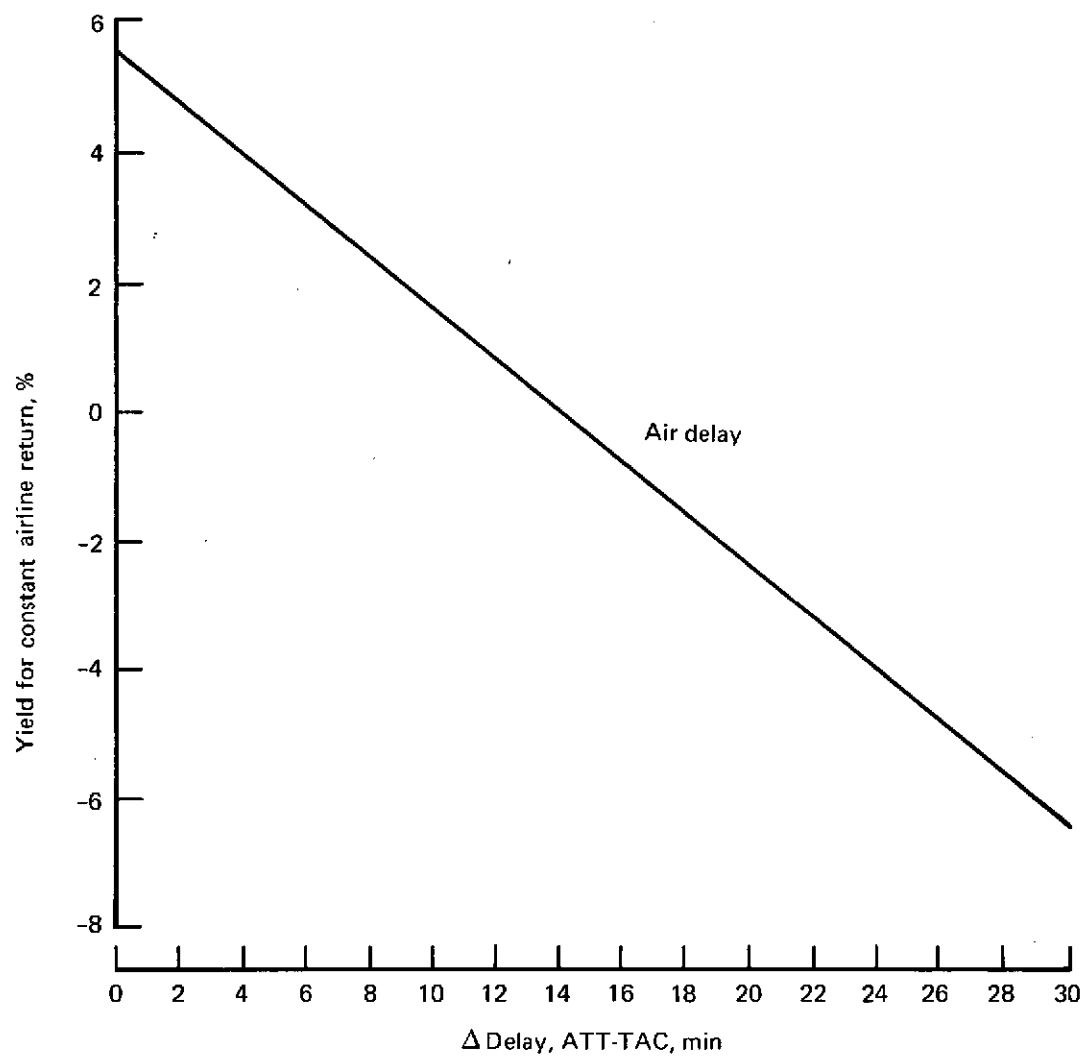


FIGURE 77.—YIELD NECESSARY TO OFFSET COSTS—TAC VS. ATT (BASELINE)

believed to be reasonable and read the percentage change in yield required if return on investment is to remain constant.

7.2.6 Sensitivity of Economic Comparisons to Fuel Price

The TAC airplane has slightly better fuel economy than ATT or the current wide-body aircraft except at short ranges. Maximum range comparison shows an advantage to TAC of approximately 5% in fuel economy. Therefore, increases in fuel price will extract larger cost penalties from ATT or CWB than from TAC aircraft. Figure 78 shows the expected increase in DOC per airplane statute mile (1.6 km) for every one cent per gallon increase in fuel price. Calculations were made on an 1850 km (1000 nmi) trip basis and would show greater penalties for ATT and CWB if longer ranges had been selected. The same figure shows the estimated annual charge in DOC per airplane based on 1550 trips per year.

The bars on the left indicate that ATT aircraft direct operating costs will increase by 4.18 cents per statute mile for every one cent of increase in fuel price, if ATT could operate with standard delay (six min airborne 14 min taxi). The CWB airplane was calculated to show an increase of 4.05 cents per statute mile. TAC, because of better fuel economy will increase only 3.88 cents per statute mile for every one cent increase in fuel price.

Delay is costly in terms of fuel consumption. Under the expected operational delay for the ATT or CWB airplane the greater fuel consuming aircraft will show increases per statute mile of 4.78 cents and 4.30 cents, respectively for every one cent increase in fuel price in comparison to the 3.88 cents per mile per cent of increase calculated for TAC at its expected delay level. See figure 78. Under expected operating conditions each one cent increase in fuel price will have a 23% more harmful effect on operating cost of ATT airplanes than on TAC. The CWB DOC will increase 11% more than TAC DOC for every one cent increase in fuel price.

Increased fuel price makes it mandatory that aircraft fuel consumption and delay be minimized. The TAC design moves toward optimum in both areas.

7.2.7 Cost of Noise-Abatement Modifications

Section 7.2.3 explained the manner in which each modification or delta was treated as a separate entity in order to be able to assign costs and benefits to each one individually. The modifications referred to as Delta 2, Low Speed Aerodynamics and Delta 3, Steep Descent were put in the TAC configuration for noise-abatement benefits. Section 7.1 discusses the benefits realized.

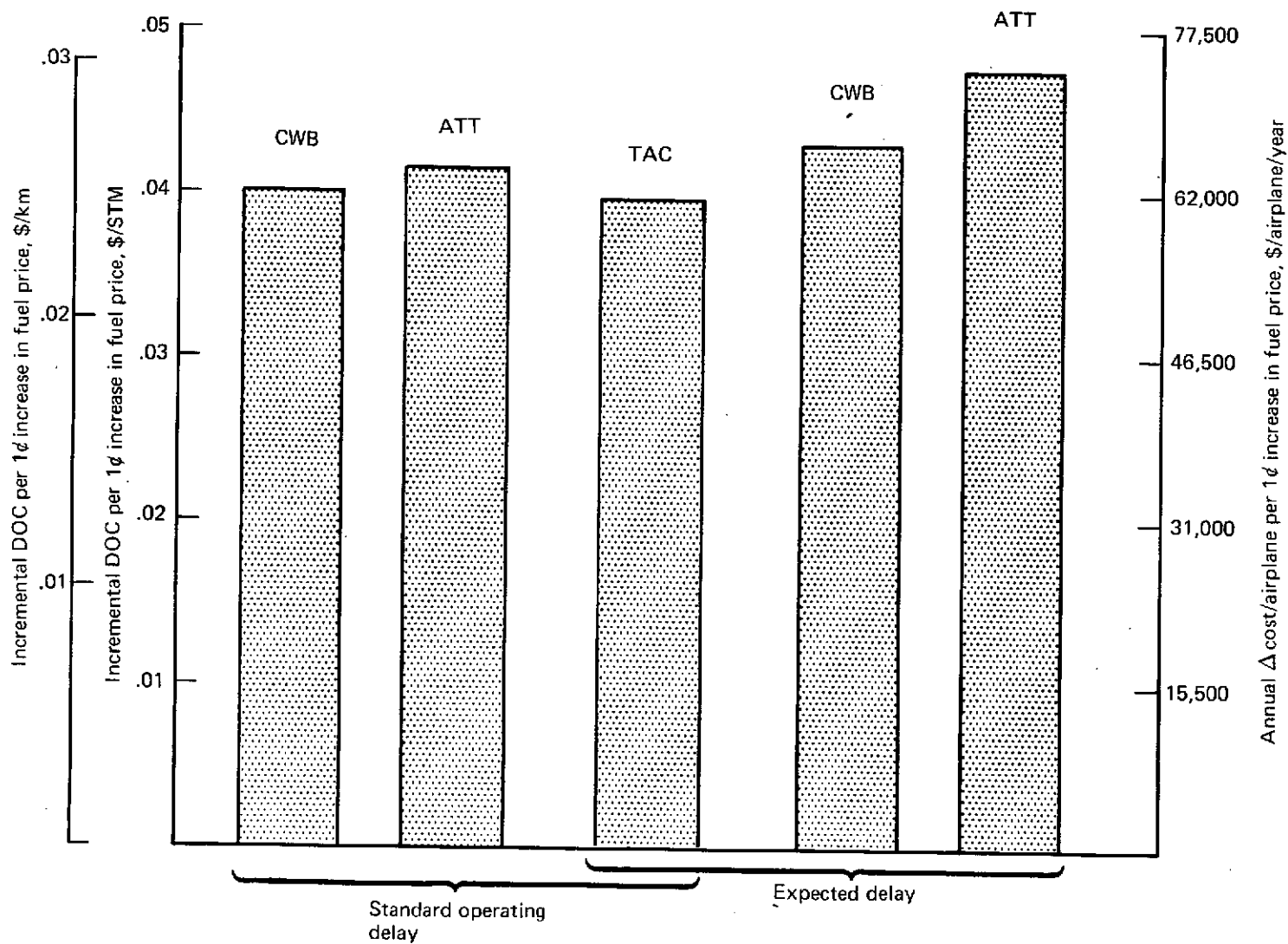


FIGURE 78.—SENSITIVITY OF DOC TO FUEL PRICE—1850KM (1000 NMI) STAGE LENGTH

Economic evaluation was made using the basic airplane with only these two noise-abatement modifications. The acronym TAC-N was applied to indicate that only the noise-reduction modifications were considered. Figure 79 indicates that TAC-N is 5.4% more expensive to operate than the baseline ATT whether compared with the standard delay or with expected operating conditions. There are no features to TAC-N which would make for delay reduction. If noise abatement modifications only were made, a penalty of 5.4% in DOC could be expected.

If, however, Delta 2 and Delta 3 are part of the whole TAC package including delay-reducing modifications, the benefits of delay reduction can be expected to more than pay for the cost of noise abatement. Figure 79 also shows the TAC DOC level under expected operating conditions which is 13% below TAC-N and 6.6% below ATT, each calculated with the expected operational delay estimated for that airplane. To make only the noise-abatement modifications would prove costly to the airlines; to include them in a package of delay reduction, noise abatement, and emission control offers the potential of applying the cost savings of delay reduction, to pay for the community benefit of noise reduction.

The two 1800 horsepower APUs in the TAC configuration are included in the TAC-N configuration, prorating costs of these items with powered wheels, the other modification requiring APU. Powered wheels were charged with 33% of the APU cost, 67% being allocated to noise abatement. The in-flight secondary power source usage of the APU is the principal cost item in the noise-abatement modifications. Therefore, any reliability improvements would reduce operating costs of the noise abatement as well as the TAC configuration (see sec. 7.2.3.2).

Alternate concepts were considered and reported in a previous section. The first concept reduced the APUs to 1200 horsepower but retained two units with in-flight usage. Table 18 below shows small economic benefit to this change. The second concept removed the in-flight usage and utilized the one remaining unit for normal on-the-ground power source as well as being utilized for powered-wheel operations. This concept is beneficial economically, making a 2.2% reduction in DOC per airplane.

TABLE 18.—ECONOMIC RESULTS: APU TRADE STUDY

Model	APU maintenance direct charges, dollars/flight-hour/2-hr flight	Maintenance complexity factor, \$	DOC, \$/SM	DOC, \$/SM	Change
TAC	23.20	151.15	2.3062	—	
APU variation 1	20.90	142.09	2.2983	0.0079	
APU variation 2	8.16	92.24	2.2547	0.0515	

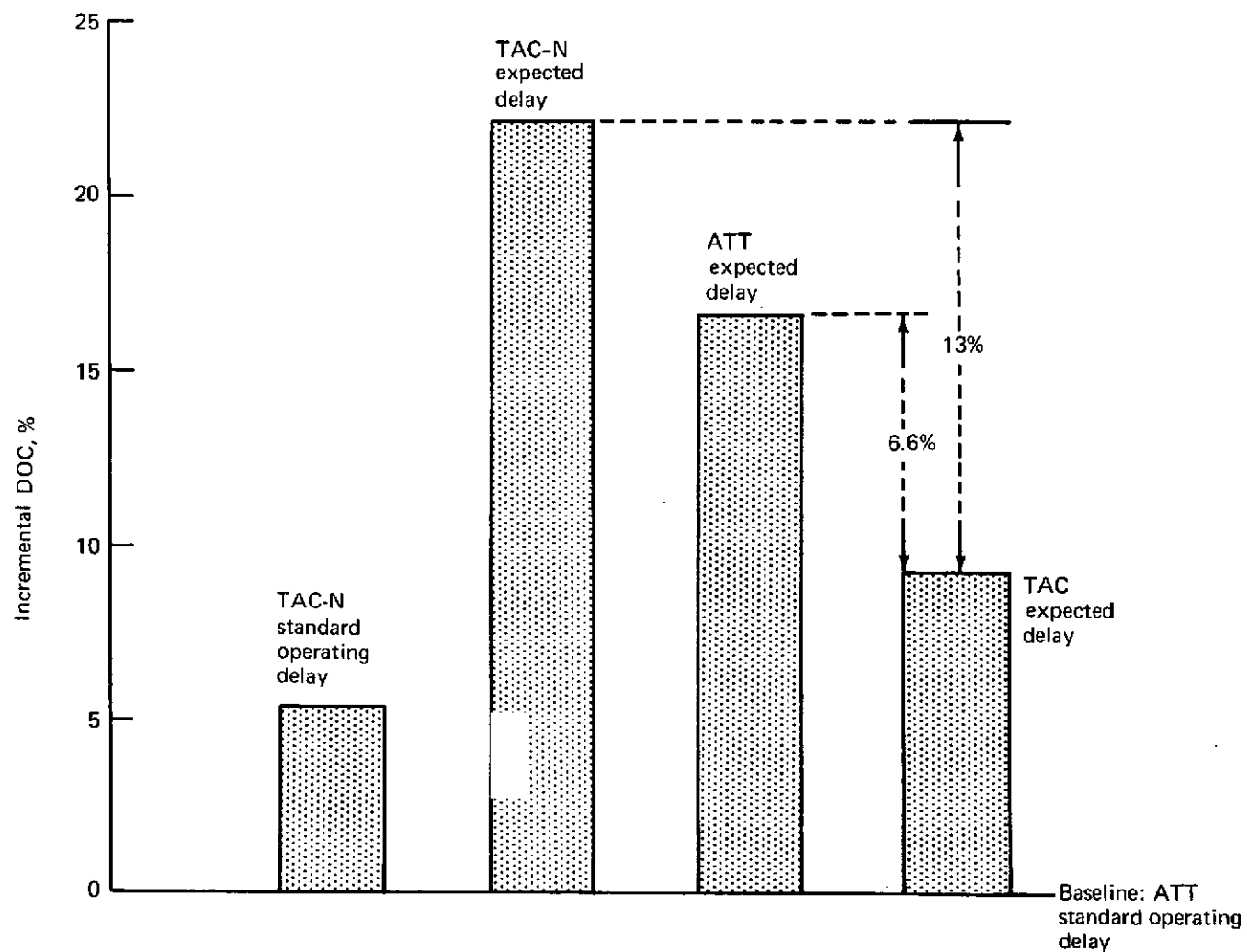


FIGURE 79.—COST OF NOISE-ABATEMENT MODIFICATIONS—DELAY REDUCTION PAYS
FOR NOISE ABATEMENT—1850KM (1000 NMI) RANGE

7.2.8 Cost of Emission-Reduction Modifications

Two modifications were included in the TAC configuration for purposes of reducing emissions, Delta 5—Powered Wheels, and Delta 8—Engine-Emission Control. As explained above, these were treated as separate entities and evaluation made of the basic airplane with only these emission reduction modifications. This was referred to as TAC-E.

Engine manufacturers were optimistic relative to progress in combustor technology that would permit significant reduction in emissions on new engine designs. Penalties in either performance or acquisition cost were negligible (+0.2% DOC). A previous section discusses these improvements and the estimated progress toward the Statement of Work goals. The same section also shows options available to reach these goals.

The first option was to assume even greater improvements in combustor technology by the engine manufacturer. Economic assessment was made *assuming* the goal could be reached with a 10% increase in acquisition price of the engines. Figure 80 shows an expected 1% increase in DOC if the goal is met in this manner.

Powered-wheel taxi operations decrease emissions since APU emissions are less than those of the main engines even under reduced engine emissions. Powered-wheel operations are expected to add 1% to DOC (see fig. 80).

Cornell Aeronautical Laboratory used 1968 (controller slow-down year) data to calculate a landing and takeoff cycle (LTO) for the Environmental Protection Agency. This cycle showed 26 min of ground operations to be average. This figure was used in the economic studies and is referred to as the EPA Cycle. A study of LAX, ORD and JFK, made during the TAC effort, indicated average taxi time at these busiest airports to be 23 min. Another Boeing study indicates that if delay were to be eliminated, taxi time could be reduced to the standard 14 min. Figure 80 indicates a 4% reduction in DOC if taxi time can be reduced to 14 min. The TAC study has not included ways and means of reducing taxi time but only points out the advantage of such reduction. Study of ground control and ground delay reduction is recommended.

The fourth option shown in figure 80 is the use of powered wheels in a no-delay taxi time. This option would minimize emissions. The reduction in taxi time would more than pay for the additional cost of powered wheels, showing over 2% lower DOC than the baseline ATT operating on the EPA cycle.

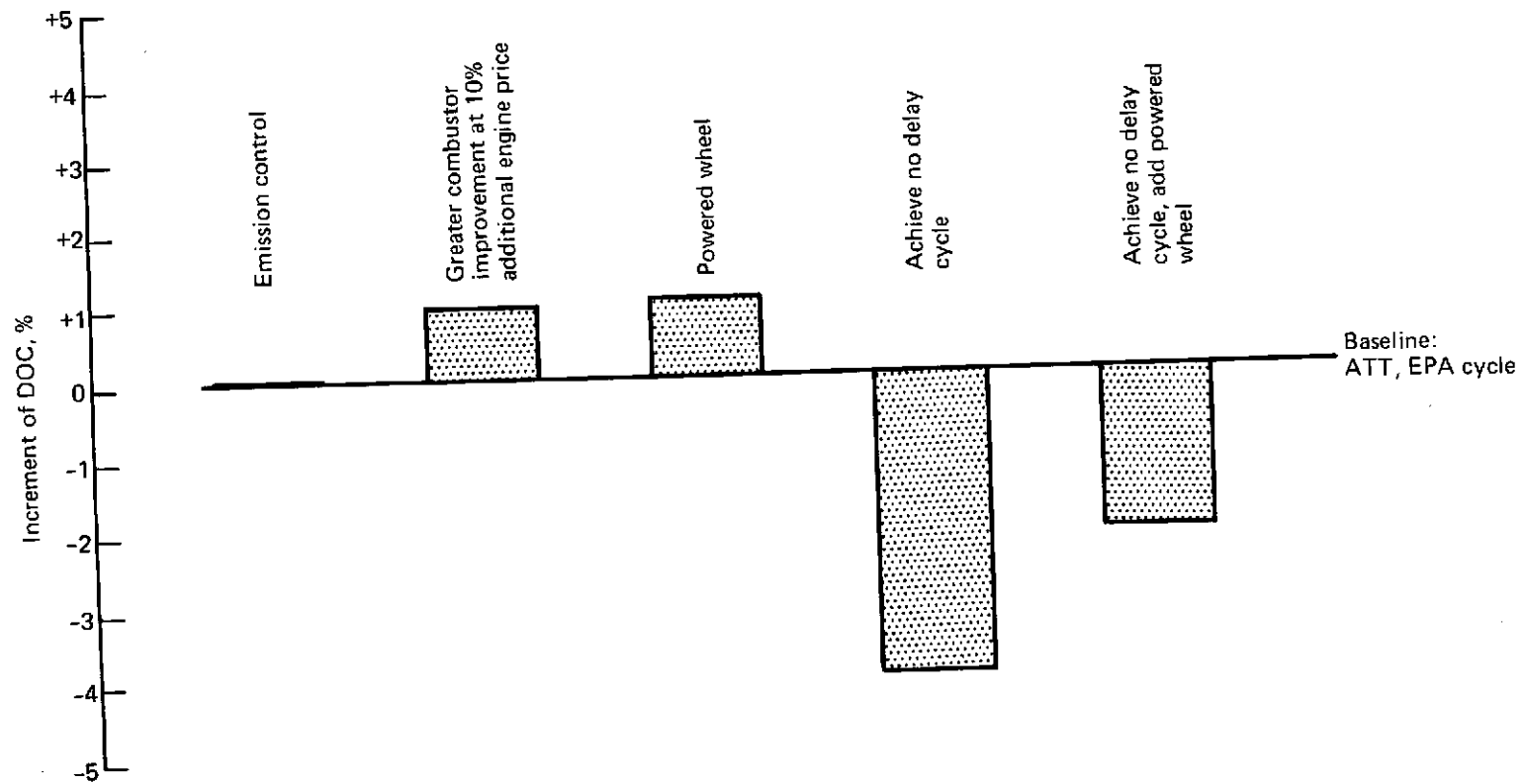


FIGURE 80.— COST INCREMENTS FOR REACHING EMISSION CONTROL GOALS—
1850 KM (1000 NMI) AVERAGE TRIP

7.3 COST/BENEFIT ASSESSMENT

7.3.1 Overview

In the first part of this chapter, the penalties to airplane performance due to design modifications improving terminal compatibility were described. The terminal compatibility benefits were also presented. In the second part, these penalties were translated into economic terms. Specifically, the component operating costs and the net present value (NPV) of the four-study airplanes were compared. This section gives a brief evaluation of the combined costs and benefits of aircraft designed for terminal compatibility.

The purpose of each modification included on the TAC airplanes was to achieve benefits in one or more of three areas: (1) delay reduction, (2) noise abatement, or (3) emission control. However, a parallel treatment of the cost-effectiveness of these terminal compatibility characteristics is difficult to develop. The problem is this. Delay costs and benefits are incurred and realized primarily by a single organization, namely the airlines. Noise and emissions present a different situation. In this case, the costs are borne by the airlines whereas such social benefits as may be achieved accrue to one or the other segments of the general public.

Using generally-accepted evaluation techniques, estimates were developed in terms of increased operations per runway, the value of time saved by the traveling public, fuel savings and increased ATC effectiveness. The benefits of noise and emissions were developed in terms of the percentage reduction of noise-affected areas and the relative reduction in tons of emissions.

To help in separating out the congestion, noise and emissions, three pseudo-airplanes are used. The TAC-C is the TAC airplane incorporating only those design modifications associated with Congestion. Similarly TAC-N and TAC-E aircraft are discussed in conjunction with Noise and Emissions. These airplanes exist in a calculation sense only since no design work supports them.

7.3.2 Cost/Benefits of Congestion Reduction

Section 7.2 shows the costs of acquiring and operating the TAC airplane and compares these costs with those of the baseline advanced-technology transport (ATT) from which the TAC airplane was derived. The same chapter gives details of the expected reduction in delay if TAC airplanes are predominant in the 1980-2000 airline fleets. Benefits, in terms of reduced operating costs to the airlines, were shown in that chapter as well as the calculated Net Present Value (NPV) for the TAC, the ATT, and the current wide-body aircraft (CWB), (see fig. 76). Figure 81 shows the expected improvement to congestion in terms of increased operations per hour per runway for the ATT as compared to the expected 60 operations per hour per runway for a TAC-equipped fleet (see fig. 75).

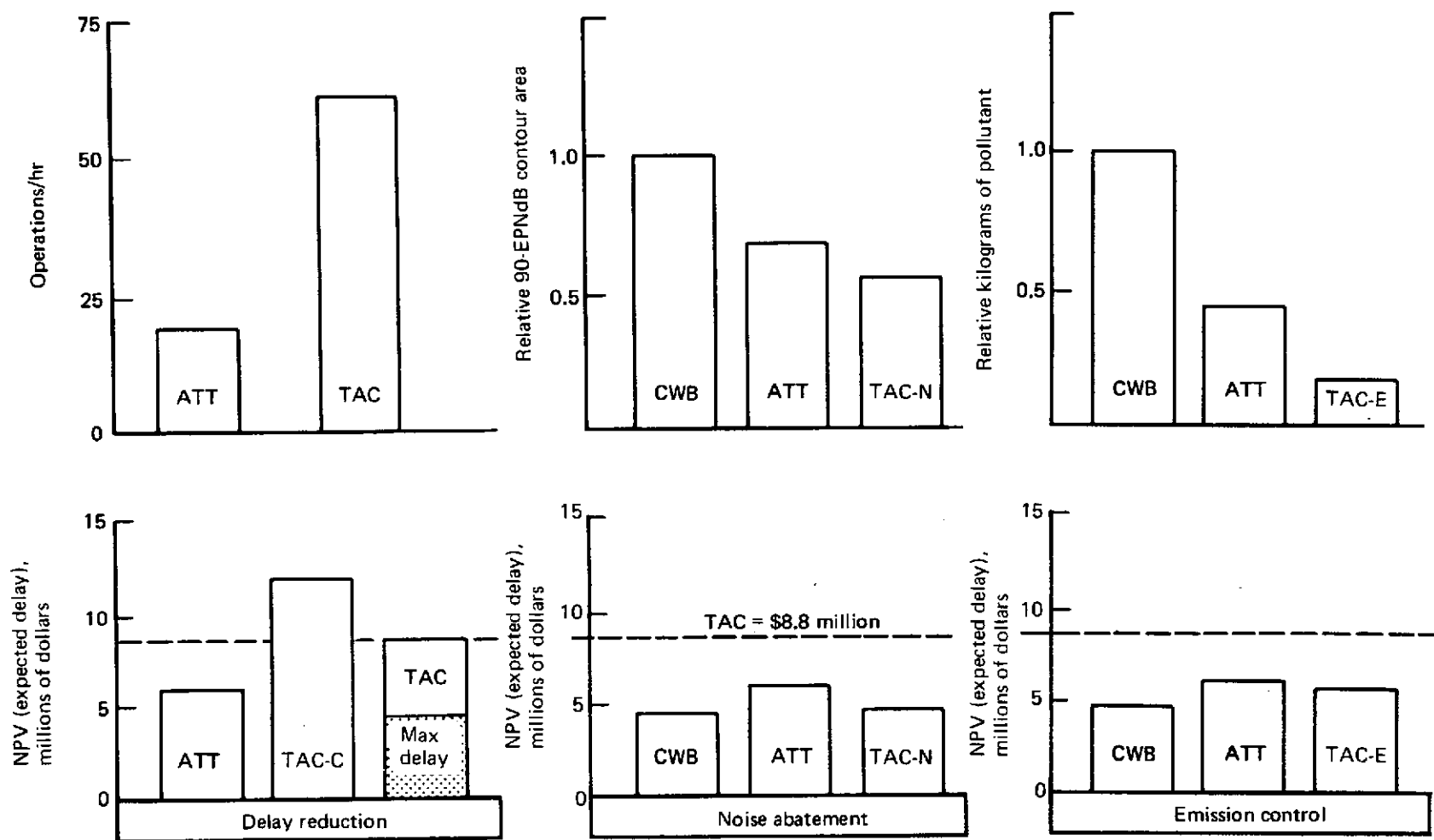


FIGURE 81.—COST AND BENEFITS SUMMARY

Costs of airline operations with the expected delay for each type of airplane were calculated. The benefits accruing to the airlines are also shown in figure 81 in the form of Net Present Value. If only congestion reduction modifications were added to the baseline ATT (TAC-C), the NPV of the airline investment in TAC-C would approach a 2:1 ratio when compared with the NPV of the baseline ATT, under expected delay conditions for each airplane.

The same chart shows the NPV of the TAC airplane including noise abatement and emission-control modifications. The TAC airplane shows over 50% greater NPV than the baseline ATT with expected delay. This value of the TAC investment is, of course, lower than that calculated for TAC-C (delay reduction only). The conclusion may be reached that delay reduction has the economic potential to offset the costs of noise abatement and emission-control modifications investigated in this study.

7.3.3 Cost/Benefits of Noise-Abatement Modifications

Noise-attenuation modifications were a feature of the baseline ATT airplane and were therefore incorporated also into the TAC airplane. The additional TAC modifications were described previously. The noise benefits, which do not lend themselves to logical monetary quantification, are realized by the surrounding community. The benefits of noise abatement shown in figure 81 are in terms of the relative area enclosed by 90-EPNdB contours for the CWB, ATT, and TAC airplanes. These data indicate a 46% reduction in the 90-EPNdB area for the TAC airplane compared to the CWB present technology airplanes. (Note the ATT airplane achieves a reduction of 32% that of the current wide-body airplane noise area.)

These benefits to the community, however, exact a price in airline operational costs. TAC-N (noise-abatement modifications only) results in a net present value nearly 25% lower than the baseline ATT. It should be noted that TAC-N has no features which would tend toward reduced congestion and therefore the calculations have been made on the longer delay expected for the CWB and ATT airplanes.

If the noise-abatement modifications are part of the total TAC package, the airline NPV for the TAC airplane is over 50% greater than that for ATT as discussed above. In other words, the economic potential of delay reduction is sufficient to offset the cost of noise-abatement modifications.

7.3.4 Cost/Benefits of Emission Control

The benefits of the modifications for emission control (TAC-E) are also shown in figure 81. It is estimated that emissions may be reduced to 17% of the present wide-body airplane evaluated.

Like noise abatement, the costs fall on one group, the benefits on another. Monetary benefits of emission reduction are difficult or impossible to calculate in a logical manner. Therefore, the technical benefits alone are shown.

The airline costs for TAC-E were developed. The NPV of an investment in TAC-E is less than 0.5% lower than for ATT airplanes. However, if the emission modifications are included with the delay reduction features of the TAC airplane, the NPV is over 50% higher than ATT as discussed above.

7.3.5 Cost/Benefit Summary

Delay reduction has the economic potential to offset costs of noise abatement and emission control. Research that leads to accomplishment of the delay reduction postulated may provide the economic base from which the social benefits of noise abatement and emission control may be financed. Taken by themselves, noise abatement is costly, emission control is moderately costly and largely dependent upon yet-to-be-proven advances in combustor technology.

7.4 TASK IV CONCLUSIONS

The principal conclusions derived from this task are:

7.4.1 Congestion

- a) Congestion-reduction airplane modifications of: outboard engine, vortex dissipator, improved avionics, higher brake capacity, etc., in sum incurred a takeoff gross weight penalty on the order of 2%.
- b) These features, in combination, would enable a fleet of like-equipped aircraft to improve runway operations by 50% to 150%.
- c) Congestion-reduction costs can be directly offset by benefits resulting from greater air system efficiency, e.g., congestion features will degrade NPV by 5.0%, however, this will be offset by estimated delay savings of 30 min/flight, increasing NPV by 31%.

7.4.2 Noise

- a) Noise-reduction airplane modifications of: drag brakes, high AR, no anti-icing thrust requirement, in combination, incurred a takeoff gross weight penalty on the order of 3% or a penalty to NPV of 9.9%.

- b) If economically acceptable, these features in combination would provide noise improvements in terms of FAR Part 36 on the order of:

Takeoff	5–7 EPNdB
Sideline	1–3 EPNdB
Approach	0–3 EPNdB

- c) Since the FAR Part 36 approach noise station is located between the two-segment approach transition point and touchdown, a footprint-type assessment of the TAC airplane is useful. Results show a 90-EPNdB contour area reduction of 20% for a heavily-treated nacelle or 80% for a peripherally-treated nacelle when the two-segment (nine-degree/three-degree) path is compared to the conventional 3-degree glideslope.
- d) The TAC airplane would easily handle a 4-degree approach path under essentially all-weather conditions. Such a glideslope could provide two to three EPNdB additional improvement on approach.
- e) Comparison of the TAC airplane, incorporating only peripheral treatment but utilizing its improved takeoff and approach paths, with the extensively-treated ATT showed about equivalent 90-EPNdB contour areas. The result suggests that the two noise-reduction methods should be viewed as alternatives rather than in combination.

7.4.3 Emissions

- a) Emission-reduction airplane modifications of: advanced combustor, revised engine cycle, and APU-powered wheels, in combination, incurred a takeoff gross-weight penalty of <1%, corresponding to a decrease in NPV of 5.8%.
- b) On a per-cycle basis, these modifications, in sum, provide the following pollutant-reduction percentages for the TAC airplane:

	RELATIVE TO	
	CWB	ATT
CO	70–80	50–65
HC	90–95	85–90
NO _x	75–85	25–40

- c) If the assumed engine combustor advanced can be achieved with no penalty in performance or cost, then a powered wheel-type system is a noncompetitive design approach.

- d) It is not clear whether the net impact of the aircraft pollution control modifications will provide negligible or enormous benefits to airport/community air quality.

7.4.4 General

- a) Relative to the baseline ATT airplane, which has a 25% advantage in NPV over the CWB, the following penalties are incurred if standard ATA delay levels are considered for all airplanes:

TAC	21.4%
TAC-RTOL	30%

- b) If account is taken of expected airborne delay, then the NPV of the ATT airplane would decrease by 52%; the NPV of the TAC airplane would be unchanged.
- c) It is clear that if these levels of delay are realized, then the TAC delay cost savings more than offset the costs incurred for noise and emission reduction.
- d) A doubling of fuel costs under conditions of expected airborne delay would decrease the NPV of the baseline ATT by 46.5%. However, the TAC airplane NPV would suffer a decrease of only 33%. In absolute terms, the resulting NPV levels would be \$3 020 000 for the ATT and \$5 900 000 for the TAC.

TABLE 19.—PRINCIPAL R&D RECOMMENDED WORK PACKAGES

Item	Approach	Ground operations	Takeoff	Cruise
Airplane	1 Wing trailing vortex research 2 Airframe noise research and control 3 Aerodynamic drag device development 4 In-flight thrust reversers 5 Landing guidance 6 Improved anti-icing techniques 7 Impact of turbulence and wind shear on airplane design 8 Noise abatement approach and landing study 9 Stopping system trades 10 Noise treatment versus noise abatement procedures 11 Engine component noise research 12 Engine noise reduction with lining/treatment	16 Engine emission control 17 Auxiliary power unit development 18 Tire technology 19 Landing gear/brake dynamics 20 Automated stopping system 21 Brake material and configuration 22 Ground steering systems 23 Reduced gate-space design techniques 24 Airframe and engine maintainability 25 Large payload airplane scheduling/marketing assessment 26 Aircraft maintenance monitor 27 Powered wheel system 28 Innovative landing gear concepts 29 Powered wheel operational assessment	38 Reduced penalty high-lift and low-noise concepts 39 Advanced, low-noise engine cycles 40 Water injection systems	41 Low cost inertial systems 42 VLF navigation 43 Impact of cruise mach constraint 44 Structural implications of outboard engine location 45 Weight implications of high aspect ratio wings 46 Guidance and control integration 47 Secondary power system redundancy 48 Airplane design/energy relationship 49 Innovative airplane concepts for TAC application 50 Advanced fuel airplane concepts (liq. H ₂)
Ground Facilities	13 Steep approach operational compatibility	30 Surface traffic control		
Passenger	14 Passenger compartment and flight deck noise	31 Passenger tolerances 32 Schedule-spreading incentives 33 Aircraft interior improvements		51 Cabin and interior noise, effect of M _{CR}
Community	15 Post-1985 noise criteria	34 Ambient air quality standards review and assessment 35 Terminal area air pollution model 36 Terminal area meteorology model 37 Pollution containment altitude		

8.0 RESEARCH AND DEVELOPMENT SUMMARY

Since the primary purpose of the TAC Study was to identify necessary research and development programs, these have been emphasized and made readily available for reference by being placed in a separate volume, Volume II of this document. Fifty recommended research items are detailed and organized by the applicable phase of airline operations. They are also cross-referenced by technology and by the part of the airplane affected. These are listed in table 19.

Each research item contains a statement of the potential payoff, the current state of readiness, and the recommended action. In addition, an estimate of the magnitude of the cost and duration of each item is given. Many of these items could be carried out using the NASA Research Support Flight System (RSFS), a 737 equipped with extensive avionics capability, and are similar to activities planned for the RSFS Program; no attempt was made to coordinate the TAC Study research recommendations with the RSFS Program or with other NASA or DOT research programs.

The research items were identified during the study on three bases. First were those items which are directly necessary to realize the airplane modifications needed for terminal compatibility, such as improved engines or better stopping systems. Secondly, areas were uncovered in which our knowledge is inadequate to accurately assess the problem or to understand the theoretical limits on improvements, as in the case of airframe noise or the effect of airplane emissions. Thirdly, while the study concentrated on necessary airplane developments, it was obvious that some of the companion developments in the ATC and airport systems are essential, and require research.

Some of the items recommended in this study are similar to earlier recommendations made in the previous ATT study. Most of the other research items identified in that study, those unrelated to terminal area compatibility, are still required, and in fact in some areas the terminal compatible airplane would not have been possible without the assumption that ATT-recommended research will have been successfully completed by the time the TAC airplane is built.

As indicated throughout this report, it is essential to the future of the air transportation system, and to the communities which it serves and which are affected by its operation, that money be invested in research. Although difficult to quantify, the benefits to the entire community of these airplane improvements are large. On a more tangible level, figure 82 compares the savings that can be realized directly by the airlines and their customers, in terms of reduced delays, with the research and development costs.

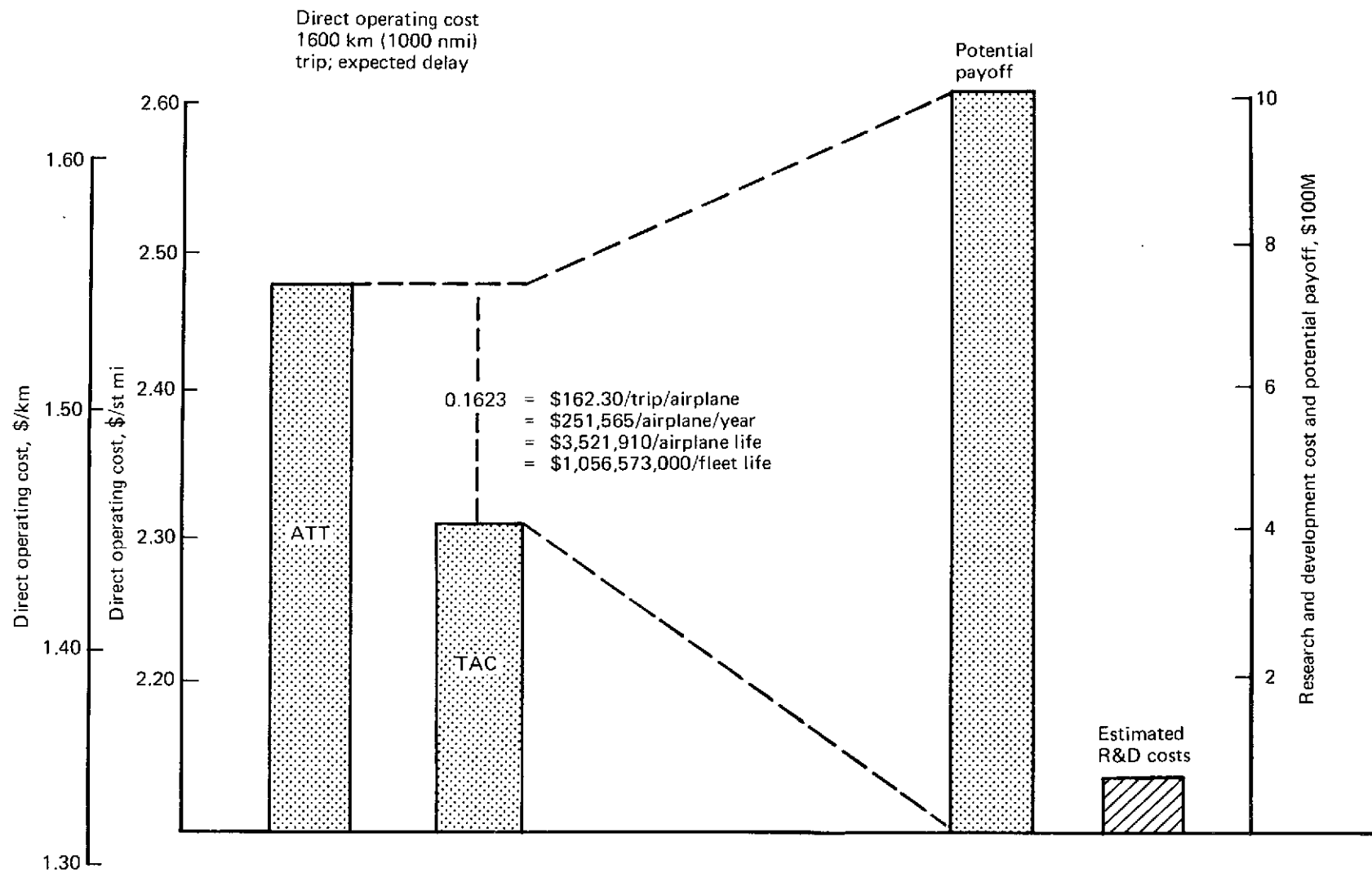


FIGURE 82.—ECONOMIC IMPACT OF THE RESEARCH AND DEVELOPMENT PROGRAMS

9.0 CONCLUSIONS AND RECOMMENDATIONS

A broad study has been completed which forecast expected, unconstrained air traffic growth and the potential impact on airplane and airport compatibility to the year 2000. Particular emphasis was placed on congestion, noise and emissions. Four aircraft were configured in the course of the study to help understand the role of proposed design modifications. An economic assessment was made of these changes. To the extent that the study was broad, sufficient detail was developed to satisfactorily achieve the program objective of identifying appropriate aeronautical research and technology areas. A quantitative summary was given in figure 2. Principal conclusions were:

- a) With respect to air-transport congestion:
 - 1) The results show that if no corrective steps are taken, major urban airports face intolerable levels of peak-hour delay if the forecast travel demand is to be handled. These peak-hour delays are symptomatic of the gradual binding up of major portions of the air transportation system. This was in spite of predicted use of increasing numbers of 400-passenger and eventual introduction of 800-passenger aircraft on certain high-density routes.
 - 2) One way to improve this situation is to upgrade runway usage efficiency by increasing runway operation rates. A principal obstacle to this goal is the required separation distance between aircraft dictated by wing-tip vortex (wake turbulence) constraints.
 - 3) Design approaches to reduce tip vortex impact are currently under investigation but no effective control method has yet been demonstrated. One potential approach, air ejection using the engine-jet exhaust, was evaluated in this study. This approach, when supplemented by other airplane modifications to enable more rapid removal of aircraft from the runway and permit more parallel runway use, can improve runway operations rates by 100% to 150%.
 - 4) Airplane penalties to introduce these design changes have been estimated at about 2% in terms of takeoff gross weight. This corresponds to a penalty in DOC of about 2.5%.
 - 5) An assessment of the cost savings achievable by congestion reduction have shown potential improvement to operating costs of about 15%. This savings more than compensates the cost of congestion-reducing airplane features. In fact, the savings more than offset the total cost of all the congestion, noise, and emission modifications made to the TAC airplane, if necessary steps are taken to implement new aircraft on a fleet basis.

- 6) No significant market potential was shown for a (long-range) TAC airplane with reduced takeoff and landing capability. If such an aircraft were to be configured, the use of a conventional mechanical-flap system would be more cost effective than any currently known propulsive-lift concept.
 - 7) Critical technology areas identified include aircraft wake turbulence control techniques; up-grading of the aircraft avionics system in the navigation, guidance and display areas for both airborne and ground operations; and, an improved assessment of passenger tolerance to several airplane operational changes required to improve runway operation rates.
 - 8) The proposed design solution of increased runway usage efficiency still contains major questions. Foremost among these are safety and ground handling of the increased number of airplanes. Further studies to resolve these questions are strongly recommended.
- b) With respect to community noise:
- 1) Unlike congestion the future noise impact at major airports was shown to decrease as a result of: (1) the natural phasing out of existing, relatively noisy, first-generation jet aircraft, (2) increased use of current, noise-designed, state-of-the-art aircraft, and (3) introduction of advanced aircraft of FAR Part 36 noise calibre. Furthermore, under appropriate noise-improvement assumptions for the current fleet, it was shown that new aircraft, introduced at levels of 10 EPNdB below FAR Part 36, would reduce noise-impact areas surrounding major airports to about the size of the airport area itself.
 - 2) Previous studies using the same baseline airplane as the current contract had shown that reduction of aircraft noise using increased acoustic treatment could achieve noise levels of 10 EPNdB below FAR Part 36. Greater noise-reduction levels were also projected but at disproportionately more penalty.
 - 3) The current study showed potential noise improvement due to modifications of the airplane takeoff and descent flightpath. A five- to seven-EPNdB improvement at the FAR Part 36 takeoff noise station using thrust cutback was obtained relative to the baseline ATT airplane. This was achieved by improved low-speed aerodynamics. This aerodynamic improvement also provided two to three EPNdB reduction on approach; however, this was offset by an independent design modification adopted to improve wake turbulence.

- 4) Noise abatement steep approach capability required large innovative deployable-drag brakes together with advanced navigation guidance and cockpit display avionics. A 9-degree/3-degree two-segment approach goal was defined. Noise improvement, assessed in terms of the 90-EPNdB contour area showed that steep approaches do not offer substantial benefit if used in conjunction with a heavily-treated engine installation. However, if used in conjunction with a peripherally-treated engine nacelle, an 80% approach noise-contour area reduction was shown. Furthermore, with only peripheral treatment, but with the improved takeoff and approach path capability, the TAC airplane 90-EPNdB area was equivalent to the baseline ATT airplane with extensive acoustic treatment. No attempt was made in this study to establish or evaluate optimized noise abatement flight paths.
- 5) Airframe noise is a key limiting technology with respect to overall airplane noise on approach. Insufficient design experience with respect to the proposed steep-descent drag brakes is also a technology weakness. These problem areas are very much related. Work was recommended on both topics as well as expanded fundamental investigations of: (1) improved methods of reducing engine source noise and (2) ways to increase attenuation system performance.
- 6) Initial indications are that the use of high flap settings for both takeoff and approach will generally not be used in practice because of noise restrictions. More detailed assessment of what design advantage can be taken of this situation is required.
- 7) Airplane penalties for incorporating the improved flight path capability for both takeoff and descent were established at 3% takeoff gross weight. This corresponds to increased operating costs of 3.3%. This increment in DOC compares with the 4.2% increase incurred by increasing the level of nacelle treatment from peripheral to that required to achieve 10 EPNdB below FAR Part 36.
- 8) Major questions have been raised but not resolved as to whether the extensive acoustic treatment incorporated in the baseline ATT airplane and retained for the TAC airplane is the most satisfactory approach to noise control. This study has shown that rather than reinforce each other, the use of extensive treatment is essentially redundant to improved flight-path capability. Moreover, a study of advanced, low-noise engine cycles has recently been completed by the engine manufacturers. These cycles have not been considered in the current study. A detailed assessment of the best approach to advanced aircraft noise control considering options between treatment, cycle and optimized flight path, is therefore highly recommended.

- c) With respect to engine emissions:
- 1) Aircraft emissions today constitute a very small percentage of the total overall pollution question. This study has shown that even within the immediate airport vicinity, emission sources today are about evenly divided between aircraft and automobiles. Projected future automobile emission controls could alter this balance. An assessment of satisfactory emission levels of aircraft engines is hampered, however, by lack of ability to relate such levels accurately to ambient air-quality standards.
 - 2) Future airport pollution trends can be significantly influenced by potential improvement to combustor and other technologies. A somewhat-different picture is seen for CO and HC emissions on the one hand, and NO_x on the other. The history of previous engines shows technology trends favorable to reduced CO and HC but unfavorable to oxides of nitrogen. This study has shown:
 - (a) If no improvement is made to combustor technology beyond that exhibited by the JT9D/CF6 engine class, then airport tonnage levels for CO and HC will initially drop off due to reduced automobile emissions. Increased air traffic will reverse this trend around 1990. Tonnage levels of oxides of nitrogen will show a continued increase.
 - (b) Airport pollution tonnage levels for CO/HC and NO_x can, in year 2000, be reduced by about 50% if projected advanced technology combustor concepts can be realized and installed on the post-1985 generation of new aircraft.
 - (c) Reductions in airport tonnage levels of 30% for CO and HC can be achieved if airport/aircraft ground congestion can be eliminated. Oxides of nitrogen would be relatively unaffected by this, however.
 - (d) In both cases (advanced combustors or reduced congestion) it is unclear what effect the pollutant tonnage reductions will have on ambient air quality.
 - 3) Ignoring the question of air quality, several means to reduce aircraft engine emissions have been studied including: improved combustor technology; aircraft taxi operations using a powered wheel; and, projections of reduced ground delay. Relative to an existing current wide-body airplane, a TAC airplane taking advantage of all of these would, during a given landing/takeoff cycle, show reductions of 80% for CO, 90% for HC, and 84% for NO_x.

- 4) Combustor improvements for new, advanced engines have been estimated by the engine manufacturers in informal discussions to incur negligible weight, performance or cost penalties. Under these conditions the powered-wheel device, which incurs a modest penalty of less than 1% TOGW, is nevertheless non-competitive. Study estimates show however, that a 10% increase engine cost could cause a net effect on operating cost equivalent to that of the powered wheel. As previously noted, cost *savings* result from reduced ground congestion.
 - 5) Importantly, the powered wheel offers potential design flexibility which may prove convenient to control NO_X emissions. This occurs as follows. Many projected combustor advancements reduce NO_X emissions at the expense of increasing CO and HC, and vice-versa. This study has shown that the powered wheel, while ineffective in controlling NO_X, is quite effective in reducing CO and HC tonnages. Thus the powered wheel and advanced combustor might be properly regarded as complementary rather than competitive design approaches, allowing the latter to be biased in favor of NO_X control.
 - 6) Continued and increased development of low pollutant engine combustor concepts is deemed critical. Development and proof-of-concept of the powered-wheel design approach is considered very desirable.
 - 7) The major question in the emissions area was judged to be how much emission tonnage is required or warranted for satisfactory air quality? Extensive analysis and experimental work will be required to help answer this point.
- d) In general:
- 1) This study considered congestion, noise and emission improvement achievable by direct design modification to the airplane. This approach is useful to achieve the contract goal of identifying appropriate aeronautical research and technology. However, solutions to terminal area compatibility other than airplane design obviously exist and in many cases may prove to be necessary or possibly more economically desirable. The current study is correctly viewed as only providing part of the required information necessary to deal with this broader question. In the opinion of the contractor, this broader study would be highly desirable and of timely value.
 - 2) The question of aircraft fuel usage and energy expenditure was not within the scope of this study. Nevertheless, some of the study results exposed potential conflict between the requirements for terminal compatibility (e.g., noise reduction) and energy conservation. Potentially-compatible design solutions which are conceivable

have not been explored. In the opinion of the Contractor, the relationship of energy usage to airplane design is a fertile ground for extensive future effort.

The improved airplane qualities considered in this study are rational projections. However, it is important for the reader to understand completely that implicit in these projections is the assumption of extensive research effort followed by sufficient development to demonstrate technology readiness. *In the absence of R&D expenditure, the projections shown have no basis whatsoever.*

REFERENCES

1. Final Report—Study of the Application of Advanced Technology to Long Range Transport Aircraft (two volumes). Contract NAS1-10703, May 1972.
2. Industry Report, Airline Airport Demand Forecasts. ATA, July 1969.
3. The Boeing Company: Study and Concept Formulation of a Fourth Generation Air Traffic Control System. DOT-TSC-306, November 1971.